THE EVALUATION OF A PASSIVE MICROWAVE-BASED SATELLITE RAINFALL ESTIMATION ALGORITHM WITH AN IR BASED ALGORITHM AT SHORT TIME SCALES

Robert Joyce¹, John E. Janowiak², Phillip A. Arkin³, Pingping Xie²

¹RS Information System, Inc.  
²Climate Prediction Center/NCEP/NOAA, Suitland, MD 20778 USA  
³ESSIC, University of Maryland, College Park, MD

ABSTRACT

Recently, rainfall derived from low earth orbiting satellite passive microwave sensor (PMW) retrievals and geostationary satellite window channel InFrared (IR) data have been combined in a unique manner in order to develop the CPC morphing (CMORPH) technique in which the IR is used only as a means to spatially and temporally transport the rainfall features. CMORPH uses motion vectors derived from half-hourly interval IR imagery to propagate the relatively high-quality precipitation estimates derived from PMW data. At a given point, the shape and intensity of the precipitation features are modified (morphed) during the time between PMW sensor scans by performing a time-weighted linear interpolation between PMW derived estimates that have been propagated forward in time in from the last available PMW observation and those that have been propagated back in time from the next available PMW scan. This process yields spatially and temporally complete PMW-derived precipitation analyses, independent of the IR temperature field for estimation purposes.

The possibility of extending the CMORPH analyses back in time – perhaps back to the early to mid 1990’s, is desirable. One of the limiting factors is the availability of sufficiently dense PMW coverage progressing backwards from current time. A shortcoming of the CMORPH method even with the present PMW sensor equipped satellite constellation (at the time of this writing) is that when precipitation forms and dissipates over a region between overpasses by PMW instrumentation it will not be detected. Other situations include when IR derived PMW rainfall propagation vectors used in CMORPH are not correct or when the morphing of both the forward/backward in time propagated PMW rainfall does not match the actual building and decaying processes of the actual rainfall complexes. In order to supplement the CMORPH rainfall estimation, a method is presented in which rainfall derived from a geostationary satellite IR-based PMW/IR combined sensor type algorithm called IR frequency (IRFREQ) is compared with CMORPH at small temporal and spatial scales. The skill/error of the two disparate PMW/IR combined sensor type algorithms will be evaluated for dependence in temporal distance from PMW scan, earth location, surface type, season, and PMW sensor type.
1. INTRODUCTION

Recently, rainfall derived from low earth orbiting satellite passive microwave sensor (PMW) retrievals and geostationary satellite window channel InFraRed (IR) data have been combined in a unique manner in order to develop the Climate Prediction Center (CPC) morphing (CMORPH) technique (Joyce et al. 2004) in which the IR is used only as a means to spatially and temporally transport the rainfall features. Half-hourly analyses of the PMW-based CMORPH at a grid resolution of 8 km (at the equator) have been produced operationally since November 22, 2002. Validation of CMORPH analyses indicate that the method is consistently better than blended IR-PMW rainfall estimation techniques that use IR-derived estimates of rainfall when PMW data are not available (Joyce et al. 2004). Furthermore, CMORPH estimates perform better than mere composites of PMW precipitation analyses and sometimes perform better than radar. This indicates that the propagation and morphing procedures has positive impacts compared to simply compositing all available PMW information.

There are several CMORPH related issues that CPC continues to investigate. The possibility of extending the CMORPH analyses back in time – perhaps back to the early to mid 1990's, is desirable. One of the limiting factors is the availability of sufficiently dense PMW coverage progressing backwards from current time. A shortcoming of the CMORPH method even with the present PMW sensor equipped satellite constellation (at the time of this writing) is that when precipitation forms and dissipates over a region between overpasses by PMW instrumentation it will not be detected. Other situations include when IR derived PMW rainfall propagation vectors used in CMORPH are not correct or when the morphing of both the forward/backward in time propagated PMW rainfall does not match the actual building and decaying processes of the actual rainfall complexes. A method is presented in which rainfall derived from a geostationary satellite IR-based PMW/IR combined sensor type algorithm called IR frequency (IRFREQ) is used to supplement the PMW-based CMORPH estimates for these situations to create the CMORPH and IR precipitation estimation (CMORPH-IR) algorithm.

2. CMORPH

a) Rainfall Mapping

The ½ hour time interval and 0.0727 degree latitude and longitude (8 km at the equator) grid resolution was selected to produce spatially complete global (60°N-60°S) PMW precipitation analyses. The grid must be small enough to represent the propagation of rainfall systems in half hourly increments. Within PMW swaths regions, 0.0727 latitude/longitude grid points are populated with the nearest rainfall estimate, separately for each satellite. Then for each half hour, satellite rainfall maps are combined by sensor type (TMI, SSM/I, AMSU-B) and saved to separate files. The half hourly rainfall maps for each sensor type are then combined. In regions of overlap, TMI is used first, then SSM/I if no estimate from TMI is available, and finally AMSU-B. Developed at NCEP/CPC, these estimates are known as microwave combined (MWCOMB) rainfall. Each pixel in the half hourly analyses is tagged with a satellite identification representing the orbiter used to produce the estimate. The NESDIS Satellite Services Division (SSD) daily Interactive Multi-sensor Snow and Ice Mapping System (IMS) product is used as the PMW rainfall snow/sea-ice screening device.

b) Propagation Vector Derivation

The availability of global ½ hourly IR data makes these data attractive to use as a means to propagate PMW derived precipitation, producing spatially and temporally complete global precipitation analyses. Since the IR data provide good measurements of cloud top properties, IR
data can be used to detect cloud system movement such as the WINDCO (Smith and Phillips, 1972) method. Dills and Smith (1992) devised a specialized cloud relative motion tracking technique using geostationary IR and visible data. The purpose for computing cloud system advection vectors (CSAVs) for CMORPH is to propagate PMW derived global rainfall each half hour. This requires total automation, and precludes the use of visible imagery.

Figure 1. IR-derived zonal half hourly cloud system vectors (top), meridional (middle) and the maximum spatial lag correlations (bottom) for 20 UTC 7 March, 2004. Positive zonal (meridional) propagation values are westerly (southerly) in units of 0.0727 lat/lon increments per 30 minutes.

The direction and speed of cloud tops as detected by satellite IR may not always correlate well with the propagation of the lower precipitating layer of the system. An optimal spatial lag correlation scale would be large enough to include the sharp contrast of the cloud shield edges with the earth’s surface thus helping to focus on the motion of the entire cloud system, however not large enough to miss the variability of the steering currents that provide propagation of cloud system complexes. After various tests it was concluded for this work that spatially lagging overlapping 5° latitude/longitude IR regions centered at 2.5° latitude/longitude intervals met these criteria. The lag tests are performed on successive IR images using iterative ~8 km pixel shift combinations in both zonal and meridional directions, an example provided in Figure 1. Early versions of CMORPH used CSAVs directly to propagate PMW-derived precipitation. However, it was soon determined that the west to east and south to north advection rates were too fast in the North Hemisphere mid-latitudes. To correct this, a speed adjustment procedure was developed by first computing rainfall advection vectors by spatially lagging hourly U.S. NEXRAD Stage II (Klazura, 1993) radar rainfall (mapped to the same 8-km grid). More details of deriving CSAVs and their use in CMORPH can be found in Joyce et al. (2004).

c) Microwave Rainfall Propagation and Morphing

The PMW rainfall propagation process begins by spatially propagating initial fields of 8-km half-hourly instantaneous PMW analysis estimates (t+0 hrs) forward in time, by the discrete distance of the corresponding zonal and meridional vectors. Two auxiliary fields that are maintained along with each precipitation estimate are 1. timestamp (t=0 for instantaneous) in which the units represent the time, in half hourly increments, since the scan of the PMW satellite overpass used to define that pixel and 2. satellite identification. All PMW satellite pixels (including those with zero
precipitation) within each 2.5° latitude/longitude region are propagated in the same direction and
distance to produce the analysis for the next half-hour (t+0.5 hr). Finally, if a PMW-derived
precipitation estimate from a new scan at “t+0.5 hr” is available at a particular pixel location, then
that estimate overwrites the propagated estimate and the associated time stamp for that pixel is
set to a value of zero. Otherwise, the time stamp is incremented by a value of “1”. This entire
process is repeated each half hour.

The propagation process is illustrated graphically in Figure 2. An initial 0330 GMT time analysis of
instantaneous (“t=0 hr”) PMW rainfall (Fig. 2a, leftmost plot) is propagated forward to produce
analyses at “t=0.5” and “t+1 hr” (Fig. 2a) using the IR-derived propagation vectors. This analysis is
actually propagated one more time step to “t+1.5 hr” (not shown), but in this case all values are
overwritten by precipitation estimates from an updated PMW scan (Fig. 2a, rightmost plot) that
became available at the “t+1.5 hr” time step (0500 GMT). The continuity of the propagated rainfall
clusters in the “t+0.5 hr” and “t+1.0 hr” fields can be appreciated by comparing them with the
updated PMW analysis (Fig. 2a, rightmost plot).

In addition to propagating rainfall estimates forward in time, a completely separate process is
invoked in which instantaneous rainfall analyses are spatially propagated backward in time using
the same propagation vectors used in the forward propagation, except for reversing the sign of
those vectors. Thus for the above example, the “t=1.5 hr” updated observed PMW precipitation
(Fig. 2b, rightmost plot) is propagated backwards to the “t=0 hr” time frame (Fig. 2b, leftmost plot).
When all propagated fields have been computed, the “t=0 hr” analysis that contains observed data
overwrites the propagated estimates for that time stamp. By propagating the rainfall analyses
temporally in both directions, the propagation speed and direction is improved over doing this in a
single direction (in time) only.

Figure 2. Depiction of the propagation and morphing process for a region in the South Pacific.
The analyses at 0330 GMT and 0500GMT are actual passive microwave estimates, i.e. no
propagation or morphing has been applied to these data. The 0400 GMT and 0430 GMT are (a)
propagated forward in time (b) propagated backward in time and (c) propagated and morphed.
To this point only forward/backward propagation of initial/updated PMW derived rainfall patterns, when and where PMW data are not available, has been shown. Changes in the intensity and shape of the rainfall features are accomplished by inversely weighting both forward and backward propagated rainfall by the respective temporal distance from the initial and updated observed analyses. This process is referred here as “morphing”, is represented graphically in Figure 2c. At each pixel location, the process by which the 0400 GMT (t+1/2 hr) estimate is produced (Fig. 2c, second plot from the left) involves creating a weighted mean as follows:

\[ \text{Morphed Value (t+1/2 hr)} = 0.67 \times P_{\text{forward}} (t+1/2 hr) + 0.33 \times P_{\text{backward}} (t+1/2 hr) \]  

(1)

where:

\( P_{\text{forward}} \) is the PMW rainfall estimate forward propagated from initial scan (0330 GMT)

\( P_{\text{backward}} \) is the PMW rainfall estimate backward propagated from updated scan (0500 GMT)

Similarly, the CMORPH value for the 0430 GMT analysis is computed as:

\[ \text{Morphed Value (t+1 hr)} = 0.33 \times P_{\text{forward}} (t+1 hr) + 0.67 \times P_{\text{backward}} (t+1 hr) \]  

(2)

Each CMORPH estimate’s associated timestamp and satellite identification are extracted from the propagated estimate (forward or backward) with the smallest timestamp. For CMORPH derived from instantaneous PMW information, timestamp = 0.

3. DATA USED FOR ALGORITHM COMPARISON

Instantaneous MWCOMB rainfall estimates from TRMM TMI, DMSP SSMI, and NOAA AMSU-B instruments, mapped to a half hourly 8-km grids (Joyce et al. 2004) are used as both input and validation (withheld versions only) of the CMORPH and the IR-based algorithm. Operational half hourly, global (60N – 60S), 8 km (at the equator) NCEP/CPC CMORPH rainfall estimates (Joyce et. al, 2004) are used in daily validations. The operational version of CMORPH ingests all available MWCOMB analyses as input. A timestamp attached to each operational estimate determines the temporal distance of the rainfall information used from the nearest past/future PMW scan to develop the estimate, in half hourly increments.

For skill/error evaluation purposes, a parallel version of CMORPH is also produced in the same manner as the operational version, however, 25% of the half hourly MWCOMB input rainfall analyses are withheld (in a 4 day cyclical manner) from processing. The MWCOMB that is set aside is used later as validation of the withheld input CMORPH algorithm. Due to less instantaneous PMW rainfall used as input the half hourly timestamp attached to each withheld input CMORPH estimate is generally larger on average than timestamps from operational version estimates.

Half hourly, 8-km operational IR-based (IRFREQ) rainfall estimates are produced at CPC by frequency matching 8-km averaged geostationary satellite window channel IR brightness temperatures with 8-km (MWCOMB) starting with heaviest rain rates and coldest temperatures similar to the manner employed by Turk et al. (2003). A nine hour period, centered on current processing half hour is used to determine regional and surface dependent frequency matched statistics required for attaching a rainfall estimate to each cold IR temperature. In addition, for skill/error evaluation purposes, a parallel version of IRFREQ is produced basically in the same manner as the operational version, however, the exact same 25% of MWCOMB analyses set aside in producing the withheld input CMORPH are also set aside when developing the frequency
statistics used for assigning rain rates. An extended (11-h to 12-h) period is used to determine the match-up statistics used in the withheld input IRFREQ in order to account for the amount of input MWCOMB set aside.

The withheld input versions of CMORPH and IRFREQ are kept at half hourly, however, averaged up to 0.25 degrees latitude and longitude for global validation against withheld MWCOMB rainfall. The operational CMORPH and IRFREQ versions (no input MWCOMB withheld) as well as the CMORPH-IR are averaged up to daily 0.25 degree latitude and longitude resolution for validation over the United States.

The daily CMORPH, IRFREQ, and CMORPH-IR estimates are validated using high-quality rain gauge data and radar data over the U.S. The United States rain gauge information that was used in this validation exercise is the Climate Prediction Center Realtime Daily Gauge Analysis (Higgins et al. 2000), which is composed of over 7000 stations. The “Stage II” hourly radar (Klazura and Imy, 1993) composites over the U.S. are also used as validation. For the validation results that follow, all data sets were gridded to a common 0.25 degree lat/lon daily grid.

4. METHODOLOGY

From the timestamp attached to each half hourly CMORPH estimate (both withheld and operational versions), a measure of skill and error as a function of temporal distance to nearest PMW pass can be determined if adequate validation is available. MWCOMB previously excluded as input is now used to determine the deterioration of the CMORPH rainfall estimation as a function of timestamp in the withheld input CMORPH version. There are several reasons for doing this. A global product, PMW-based CMORPH encompasses regions conducive of smoothly propagating stratiform rainfall complexes, seemingly relatively immune to infrequent PMW sampling, as well as dynamic convective regions often exhibiting little continuity in the development, decay, and propagation of rainfall complexes, cases obviously susceptible to sampling. On the other hand the frequent geostationary satellite IR sampling in IR-based IRFREQ yields relative algorithm strength for times far from PMW scan, especially in convective regions, however, a relatively poorer estimate at times when PMW sampling is already available and/or regions where cold cloud does not correlate well with rainfall. It would also lead to reason that both season and surface type would be a factor in algorithm type as well. Thus it would be impractical to use a local validation source in order to determine the relative strengths and weaknesses of IRFREQ with CMORPH algorithms.

Correlation of CMORPH (Fig. 3a, top panel) against unused MWCOMB, determined as a function of temporal distance to nearest past or future PMW scan from which information is used to develop the CMORPH estimate, is shown for timestamp 2 (1 hour from PMW scan) for the 23 June – 26 July 2004 period. The number of pairs used in the correlations (Fig. 3a, bottom panel) is determined by the number of occasions in which half hourly, 0.25 latitude/longitude CMORPH, IRFREQ, and withheld MWCOMB all exist, and at least one estimate in the group is 1 mm/hr or higher. Calculations are performed at 5 degree latitude/longitude intervals using overlapping 15 degree latitude/longitude regions, separated by surface type. As expected the highest values are over oceans where rainfall complexes exhibit a relatively more stable nature. Correlation of withheld input IRFREQ at timestamp 2 against the same withheld MWCOMB (Fig. 3a, 2nd panel from top) reveals a quite different depiction in which the highest values are restricted to the Tropics. Also the land-sea contrast found in the CMORPH validation does not appear to exist.

The validation correlation difference (Fig. 3a, 3rd panel from top) reveals the CMORPH algorithm globally dominates the IRFREQ algorithm at one hour from PMW scan but much more so over
ocean and mid-latitudes. Patterns remain the same, however correlations of withheld input CMORPH (Fig. 3b, top panel) at timestamp 3 (nearest information used 1.5 hours from PMW pass) for the same period illustrates quite drop-off from the timestamp 2 validations.

![Figure 3.a (left)](image)

**Figure 3.a (left)** Correlation of half hourly 0.25 degree latitude/longitude, withheld MWCOMB input CMORPH against withheld MWCOMB (top) 23 June – 26 July 2004. Nearest past/future PMW information used in CMORPH and IRFREQ = 60 minutes away. Same, however, withheld MWCOMB input IRFREQ against withheld MWCOMB (2nd from top). CMORPH correlation minus IRFREQ (3rd from top). Number of pairs for both correlations (bottom).

![Figure 3.b (right)](image)

**Figure 3.b (right)** Same, however, nearest past/future PMW information used in CMORPH and IRFREQ = 90 minutes away. In a contrasting manner, correlation s of withheld input IRFREQ at timestamp 3 (Fig. 3b, 2nd from top panel) is roughly the same as the timestamp 2 IRFREQ correlations. Comparing the two algorithms at 1.5-h from PMW scan (Fig. 3b, 3rd panel from top), CMORPH validation correlation only dominates IRFREQ over mid-latitude oceanic regions. The IRFREQ validates better than CMORPH in many Tropical and Northern Hemisphere land locations.

In a contrasting manner, correlations of withheld input IRFREQ at timestamp 3 (Fig. 3b, 2nd from top panel) is roughly the same as the timestamp 2 IRFREQ correlations. Comparing the two algorithms at 1.5-h from PMW scan (Fig. 3b, 3rd panel from top), CMORPH validation correlation only dominates IRFREQ over mid-latitude oceanic regions. The IRFREQ validates better than CMORPH in many Tropical and Northern Hemisphere land locations.

Since it appears that the relative validation skill of CMORPH compared with IRFREQ is highly dependent upon both time from PMW scan and earth location, the cumulative frequency of operational (all input MWCOMB ingested) CMORPH at each timestamp is investigated. The addition of TRMM TMI sampling is evident in elevating the percentage of CMORPH of timestamp 0 (Fig. 4, top panel) in the ~30–38 degrees latitude band (both hemispheres) to 20-25 percent. A timestamp 0 CMORPH estimate means that a PMW scan occurred over that region during the half hour period and the estimate is really the instantaneous PMW rainfall (MWCOMB) with no propagation. The cumulative CMORPH at timestamp 1 frequency (Fig. 4, middle panel) includes all the CMORPH that is ½ hour before and after an instantaneous PMW CMORPH estimate. Even with TRMM TMI, the dearth of PMW sampling in the Tropics is evident when viewing the cumulative CMORPH frequency at timestamp 2 (Fig. 4, bottom panel), with many regions less than 65 percent, however, near or above 75 percent for most of the mid-latitudes.
A quick measure to optimally combine the two algorithms in order to create CMORPH-IR, replaces CMORPH estimates with IRFREQ at timestamps when IRFREQ out-validates CMORPH. Corresponding with the relative algorithm validation difference plot for timestamp 3 (Fig. 3b, 3rd panel from top), IRFREQ replaces CMORPH estimates in many regions of the world including most all of the United States for timestamps older than 2. The cumulative CMORPH frequency at time stamp 2 (Fig. 4, bottom panel) is mostly 70-75 percent over the United States, however, only 60-70 percent over the Tropics, yielding an approximation of what percentage of CMORPH-IR is CMORPH/IRFREQ for many of these regions during the North Hemisphere early summer season. At each timestamp, spatial interpolation of withheld input CMORPH and IRFREQ validation correlation difference maps in poorly sampled regions is performed to determine the choice of either CMORPH or IRFREQ estimates within CMORPH-IR algorithm at the half hourly level.

Figure 4. Cumulative percentage of operational CMORPH as a function of temporal distance from nearest PMW information used. Timestamp = 0 (top), Timestamp = 1 (middle), Timestamp = 2 (bottom).

5. VALIDATION

Correlation validation of daily 0.25 degree latitude/longitude operational (all input MWCOMB ingested) CMORPH, IRFREQ, and CMORPH-IR against United States gauge rainfall analyses is presented for the 7 May – 18 June (Fig. 5, top panel) and 19 June – 27 July 2004 periods (Fig. 5, 3rd from top panel). In a similar manner, Stage II radar rainfall is used for daily 0.25 degree latitude/longitude correlation validation for the same 7 May – 18 June (Fig. 5, 2nd from top panel) and 19 June – 27 July 2004 periods (Fig. 5, bottom panel). Generally CMORPH validates better than IRFREQ against both gauge and radar rainfall for the entire period. To a lesser degree, CMORPH-IR out-validates CMORPH throughout the period, also against both measures. It is interesting to note that IRFREQ validated relatively poorly compared to CMORPH on the few days
CMORPH does as well or even slightly better than CMORPH-IR. However, from these validations, it is apparent that IRFREQ generally improves CMORPH during this late spring and early summer period over the United States. On a side note, the similarity of the performance of the gauge analyses and that of the radar as validation against all three satellite rainfall estimation algorithms gives confidence to the use of these two sources as validation tools. Overall, the radar does appear to correlate slightly higher with the satellite rainfall, however, not to a large degree.

Figure 5. Correlation of daily 0.25 degree latitude/longitude CMORPH (green), IRFREQ (blue), CMORPH-IR (red) against gauge rainfall analyses over the United States (top) for the 7 May – 17 June 2004 period. Same, however using Stage II radar radar for validation (2nd from top). Same, however using gauge for validation over 18 June – 27 July 2004 period (3rd from top). Same, however, using Stage II radar rainfall for validation (bottom).

6. SUMMARY

Because CMORPH is flexible and can incorporate precipitation information from any algorithm based on information from any instrument, the technique is highly complementary to the proposed Global Precipitation Mission (GPM). CPC looks forward to incorporating precipitation products from GPM into the CMORPH scheme. CMORPH stands to gain substantially with the availability of more passive PMW information. And while GPM may provide sampling from PMW radiometers every 3-hours, CMORPH can add considerable value to GPM precipitation products by melding them with IR data to increase their temporal resolution to 30 minutes.

PMW-based CMORPH rainfall estimation out-validates IRFREQ against instantaneous PMW rainfall over most of the globe, especially over oceans and mid-latitudes, for all half hourly estimation periods that are within one hour (timestamp <=2) of a half hourly period containing a PMW scan. For increasing temporal distance from PMW scan, IRFREQ generally validates better than CMORPH, especially over Tropics and over land.
Even with TRMM TMI, PMW sampling in CMORPH is most sparse in the Tropics, with only 60-70 percent of CMORPH estimates derived with a timestamp of 2 or less, however, mostly more than 75 percent for mid-latitude locations including the United States. Daily CMORPH-IR rainfall estimation generally out-validates CMORPH over the United States for late spring and early summer against gauge and radar analyses, especially when IR-based IRFREQ also validates well. For CMORPH-IR, there might be a better way to combine CMORPH and IRFREQ estimates at the half hourly 0.25 degree latitude/longitude resolution, for regions and timestamps when their relative validation correlations are similar.

7. REFERENCES


