Geosynchronous Microwave Observation System Simulation

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Abstract. Simulated observations by the NOAA microwave (GEM) sounder/imager demonstrate the capability of passive microwave soundings to penetrate storm systems while infrared observations are limited to the cloud top. Simulations employ MM5 model of Hurricane Bonnie, 26 August, 1998. Microwave soundings in the cloudy regions include scattering and absorption by the hydrometeors using a fast Jacobian approach that is compatible with satellite data streams.

Background. The concept of passive microwave sounding and imaging from geosynchronous orbit was first discussed in the mid-1970's, with a report on the topic issued in 1979 [1]. The first proposed geosynchronous microwave sensor concepts used channels up to and including those within the 183 GHz water vapor sounding bands [2], although concepts using precipitation-sensitive frequencies as low as 10 GHz were also studied [3,4]. These systems were all based on antennas of at least 4 meters in aperture size as a means to obtain reasonable spatial resolution at the geosynchronous orbit altitude. The 10-GHz concepts required antennas of up to ~10 meters in size. Industrial studies within Europe focused on Meteosat Second Generation [5] resulted in geosynchronous microwave system concepts employing antennas of comparably large sizes. As a result of the need to use large antennas all of these concepts required at least the full cross-sectional area available within a Titan rocket shroud for launch. The concepts that used antennas larger than 4.4 meters required either space deployment or assembly. Several such systems were subsequently identified [6-7] although none were developed beyond design studies - largely due to the high costs associated with the antenna subsystem.

In 1992 [8] it was proposed that submillimeter-wavelength channels could be used for many of the sounding and cloud/precipitation imaging applications that previously were believed to require the use of the more conventional microwave channels (183 GHz and below). The capabilities of submillimeter-wave channels for precipitation imaging were further demonstrated using airborne instruments in 1994 [9] that produced the first high-resolution imagery of clouds at the 325 GHz water vapor band. As a result of these studies it became clear that the antenna costs for geosynchronous microwave precipitation imaging and temperature and moisture sounding could be significantly reduced while retaining spatial resolutions similar to the previously proposed concepts by using submillimeter-wavelength channels. The demonstration of nadir sounding occurred simultaneously with the deployment of submillimeter-wavelength limb-sounding spaceborne radiometers under the successful NASA Upper Atmosphere Research Satellite (UARS) program.

It was thus with the notion of using submillimeter-wave channels that the Geosynchronous Microwave Sounder Working Group (GMSWG) was convened under the joint NASA-NOAA Advanced Geosynchronous Studies (AGS) program in September 1995 to develop a model for a practical submillimeter-wave geosynchronous microwave (GEM) sounder and imager. A report on the GEM sensor concept was issued in 1997 [10,11] and a preferred set of sounding and imaging channels for GEM refined in 1999 [12]. The GMSWG report detailed an attractive cost model that would permit demonstration of GEM for operational purposes under the NASA New Millennium program. It was widely recognized within the GMSWG that GEM would be a natural complement to advanced infrared and visible geosynchronous sounders on NOAA GOES platforms, providing improved cloud clearing and operational sounding and precipitation imaging within regions of opaque clouds.

Since the GMSWG report, GEM has been formally proposed to NASA for further development on three occasions [13-15]. These proposals received excellent reviews, but were not supported. Since these proposals were submitted, however, a geosynchronous microwave sensor has been 1) listed as an NWS requirement, 2) supported by the WMO, 3) recommended to NASA for inclusion in the NASA GPM by the International TOVS Working Group, and 4) included as a recommendation to NASA by NOAA in its 2002 report on operational precipitation measurement requirements. The GEM concept has also been adopted by a broad-based European coalition who have proposed it under the name GOMAS to ESA as an Earth Explorer Opportunity Mission [16,17]. Thus, a widespread level of support for either GEM or a system comparable to GEM now exists.

GMSWG follow-on studies using data from the NOAA AMSU-A/B sensors have confirmed the utility of using sounding channels to estimate precipitation rate [18, see also 19,20], thus providing a firm basis for one of the unique attributes of GEM, namely, that of providing imagery of precipitation rate at extremely short update intervals. Additional studies have included the development of submillimeter wavelength radiative transfer models to simulate GEM imagery and an airborne passive microwave system to simulate GEM [21].

Technical Description. The GEM observation principle is based on the use of three absorption bands of oxygen (54, 118 and 425 GHz) and two bands of water vapor (183 and 340/380 GHz). A series of narrow-bandwidth channels are implemented within these bands for a total of 37 channels that provide temperature and moisture profiling capability from the lower stratosphere down to ~2-5 km altitude. Owing to the wide frequency range spanned by the five GEM bands each of these bands is differently affected by liquid and ice water amount and drop size. These additional observable degrees of freedom provide information on cloud and precipitation type and amount.

The baseline GEM concept uses a 2-meter Cassegrain scanning antenna with a nominal surface accuracy of 10 m in a dual-stage scanning system. The dual-stage system consists of a slow momentum-compensated azimuth mechanism and fast nodding/morphing subreflector scanning system to provide both wide-area synoptic coverage and fast regional coverage with adaptive scan capabilities. The 2-m antenna will provide ~15 km horizontal equatorial resolution at the highest GEM frequency. Oversampling and superresolution techniques are expected to be able to improve GEM spatial resolutions by an additional ~20-30% for high-interest events such as hurricanes or localized mesoscale convection. Engineering studies by NOAA/ETL and MIT Lincoln Laboratories suggest that the size, weight, and power consumption of GEM (estimated at ~ 1.5 x 2x 2 m, 66 kg, and ~150 W, respectively) permit its incorporation onto a GOES R+ satellite bus without major modifications.

Thermal and inertial deformations are monitored by a series of sensors on the antenna structure. Phase errors caused by such deformations are actively compensated using a nodding/morphing subreflector with approximately five degrees of freedom. The subreflector also provides for high rate beam scanning over a limited range. Larger movements to change the observation sector are performed by momentum-compensated elevation and azimuth motors, although the possibility of using the satellite attitude control system in combination or as alternative is also considered. A single feedhorn path is baselined so as to provide hardware co-alignment of all feeds for the five bands. The baseline receiver uses a quasi-optical multiplexer and includes five individual radiometers modules, one for each band.

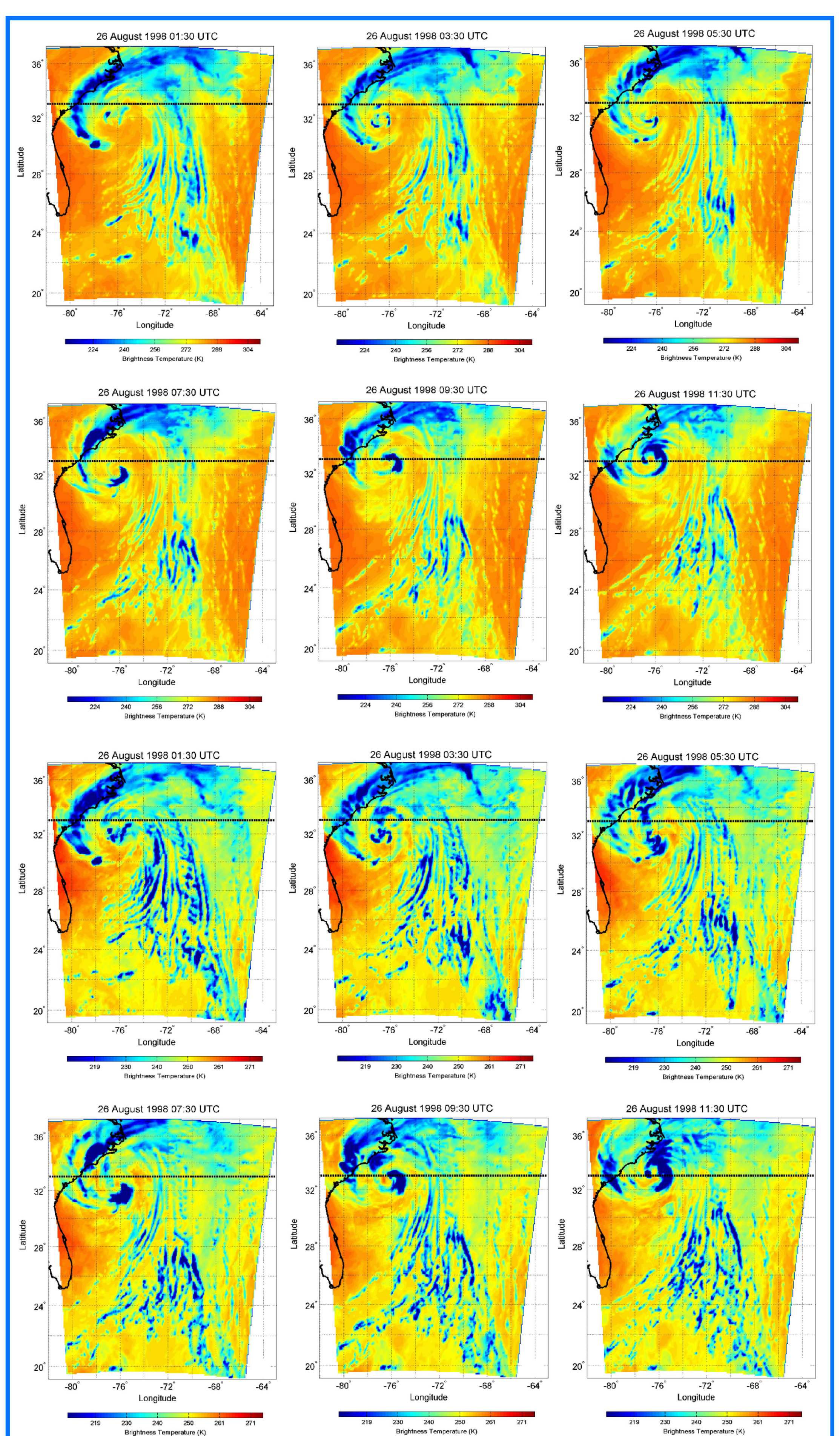

Figure 1. Diurnal cycle of Hurricane Bonnie (26 August, 1998). Simulated brightness temperature observations at the top of the atmosphere in microwave channels (top 6 panels) 183.3101 ± 17 GHz and (bottom 6 panels) 424.763 ± 4 GHz.

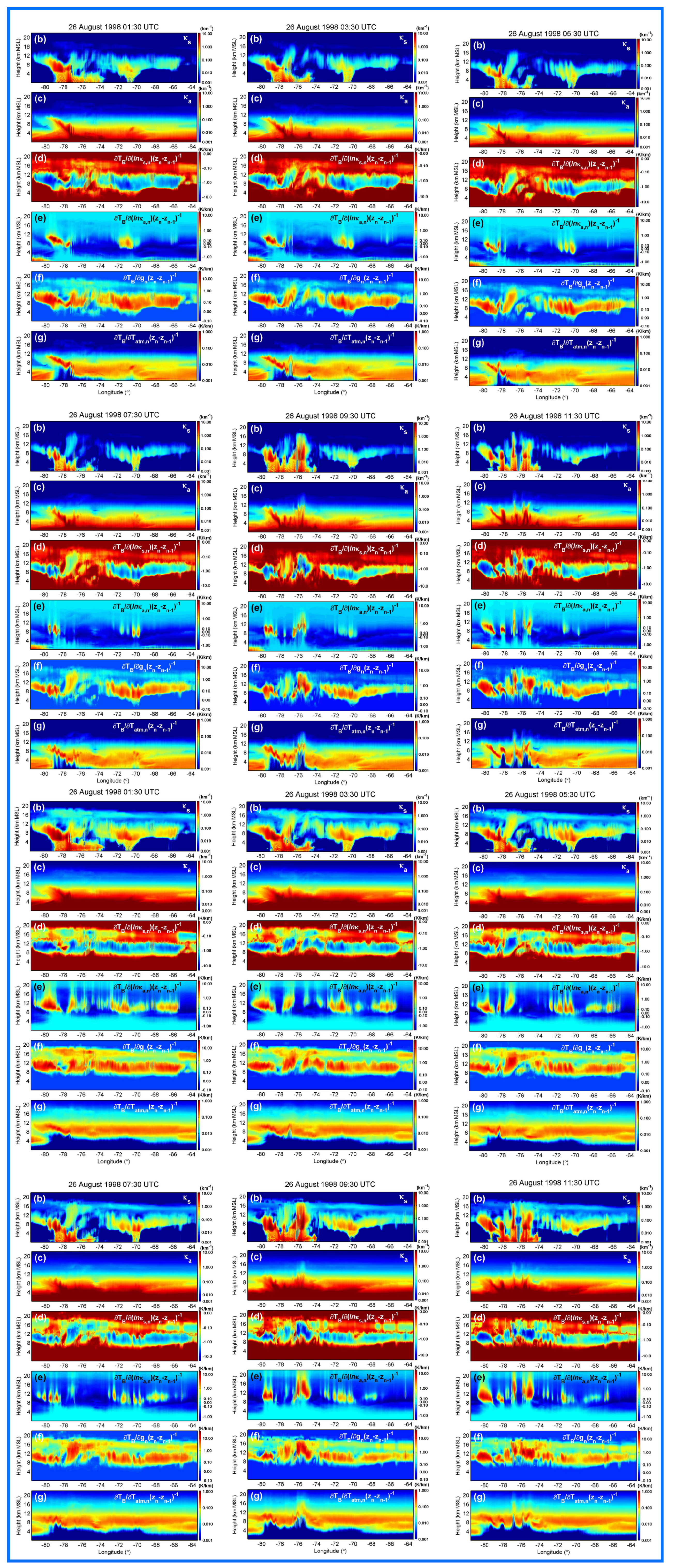

Figure 2. Diurnal cycle of Hurricane Bonnie (26 August, 1998). Vertical cross section of the Jacobian at latitude 33° North in microwave frequency 424.763 ± 4 GHz (b) scattering, (c) absorption, and normalized derivatives with respect to (d) scattering, (e) absorption, (f) scattering assymetry, and (g) temperature.

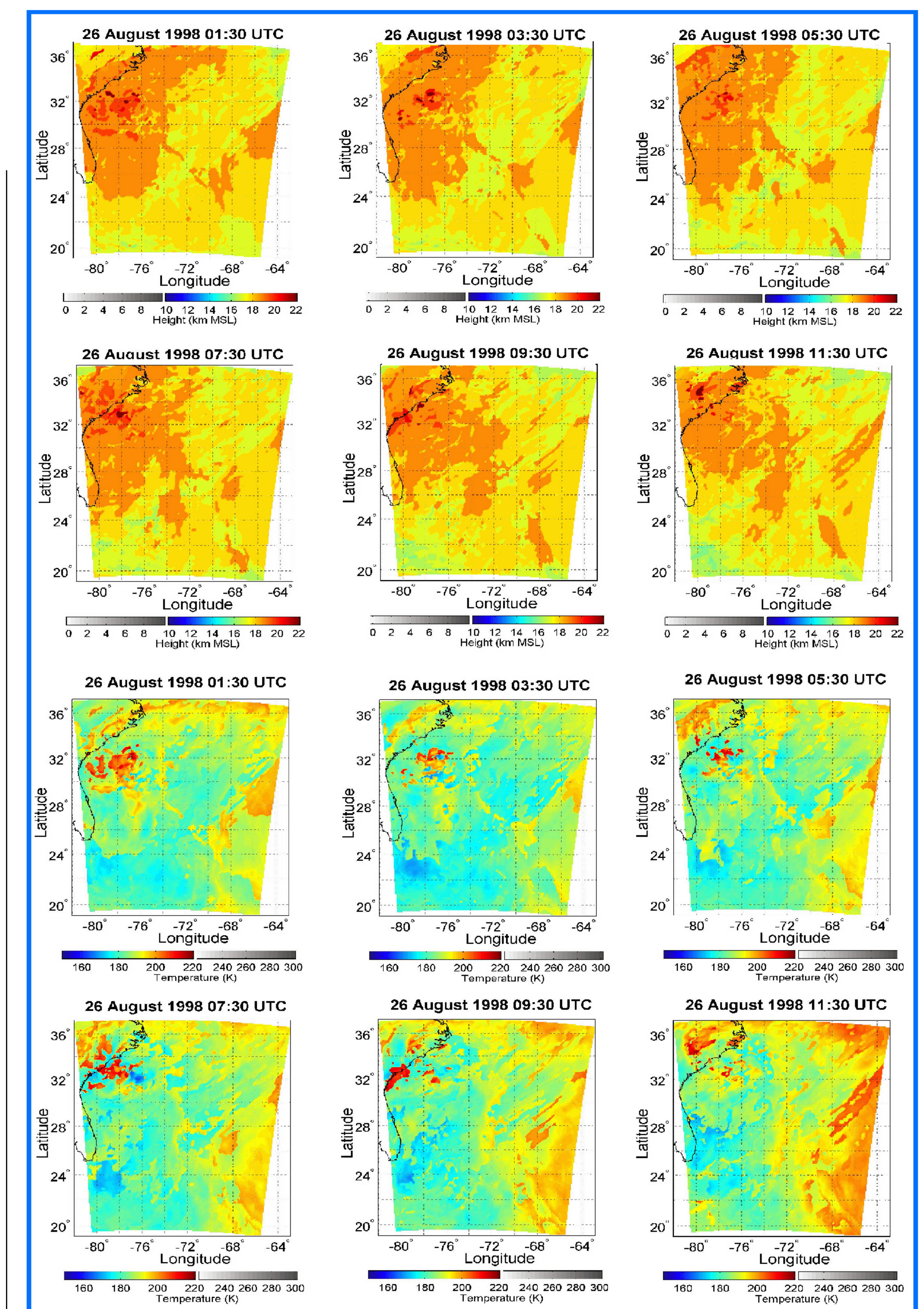

Figure 3. Diurnal cycle of Hurricane Bonnie (26 August, 1998). Simulated infrared observations (a) heights at the cloud top, and (b) temperatures at the cloud top.

Benefits of GEM. Precipitation and latent heat release are key drivers of the global hydrological cycle. The associated energy fluxes heavily influence climate patterns, which in turn can impact the severity of local weather by altering the baseline hydrological state. Because of the rapid evolution of convective precipitation events, particularly for economically significant severe storms, monitoring precipitation and latent heating is a challenging task. Existing low earth orbit (LEO) satellites cannot provide an adequate sampling frequency to capture the considerable spatial and temporal variability of precipitation events, especially over the full diurnal cycle of a system. While the current GOES system exhibits the desired temporal and spatial sampling attributes, the precipitation information available from GOES is based on IR spectra, and thus is of limited accuracy when observing over cirrus clouds. The current NEXRAD system exhibits both high time resolution and sensitivity to precipitation, but cannot provide adequate coverage in either mountainous regions or far offshore where frontal activity often drives the evolution of major coastal storm systems.

The capabilities of GEM - as outlined within the GMSWG report - are complementary to current and future NOAA ground-based and satellite systems, including POES HIRS, AVHRR, and AMSU-A/B, GOES ABS, ABI, and GIFTS, and NEXRAD. The GEM capabilities fill key data gaps in NOAA's synoptic observation system within opaque clouds and offshore regions and permit time-resolved observations of precipitation over nearly an entire hemisphere. Specifically, GEM will provide the following capabilities:

- Precipitation rate imaging comparable to AMSU, particularly for convective clouds, but on a time-resolved basis at ~15 km horizontal spatial resolution and over the complete life-cycle of the storm.
- Cloud liquid and ice total water content imaging with high temporal resolution.
- AMSU-like temperature and moisture profiling in the presence of optical- and IR-opaque clouds.
- Precipitation mapping capabilities comparable to NEXRAD but on a synoptic scale - includ ing offshore regions critical for forecasting. Observations of rapidly evolving weather fronts through clouds, without ambiguities resulting from range lift, terrain shadowing, or bright band reflection will be possible.
- Improvements in the accuracy of NEXRAD rain rate retrievals through fusion of radar and microwave data.
- Improved and unambiguous cloud clearing for either the current GOES sounder, ABS, or GIFTS.
- A means of interpolating between temporally-sparse observations of precipitation using either the NASA GPM constellation or NPOESS.
- Data for radiance assimilation containing information on precipitation location and intensity observed on the time and space scales associated with evolving precipitation systems such hurricane rainbands or mesoscale convection.
- Information on the partitioning of water condensate into clouds and precipitation for general circulation models (GCM) validation.
- Detailed spatial and temporal data on extreme events for use in detecting and diagnosing weather pat tern anomalies.

The ability of GEM to monitor precipitation evolution on rapid time scales is a very useful capability for improving the accuracy of precipitation retrievals. Many convective systems develop at particular times of day, following almost predictable diurnal cycles. By operating in a geostationary orbit, GEM will provide more accurate precipitation data than currently possible with either POES or IR-based GOES techniques. Thus, it will be possible to more accurately define the diurnal cycles in precipitation, latent heating, and the atmospheric water budget for both weather and climate studies.

Cloud and precipitation processes occur on scales that are unresolved by state-of-the-art GCMs, and must therefore be parameterized on relatively coarse scales for climate research and prediction purposes. Of particular importance in these models is the partitioning of atmospheric condensate into cloud and precipitation phases, along with the relationship between modes of condensate distribution and total and peak precipitation.

Climate is largely driven by the latent energy stored, transported, and released by atmospheric water, hence, it is essential for climate research that mechanisms for condensate partitioning be understood. Climate is also driven by cloud radiative processes which also depend on critically condensate partitioning.

Since precipitation processes vary on sub-mesoscale spatial and sub-hourly temporal bases, the observation of condensate partitioning and precipitation information is needed on similar subgrid time and space scales. Although NEXRAD can potentially be used to measure precipitation it is not sufficiently sensitive to cloud particles for condensate partitioning studies, nor does it provide accurate data in mountainous or offshore areas. GEM will provide the complimentary measurements required to help resolve partitioning questions, as well as provide improved precipitation estimates over regions inaccessible by NEXRAD.

A stringent test of a GCM is to ascertain that it produces not only the correct geographic distribution of precipitation, but also the correct spatial variability, peak intensity, and diurnal and seasonal cycles. Data for validating GCMs is thus most valuable when sampled over the complete lifetime of such weather events as rapidly evolving mesoscale convective and frontal-driven systems. By virtue of its sampling characteristics GEM will provide unique spatio-temporal subgrid data that can be used to verify the hydrologic process parameterizations within GCMs over much of an entire hemisphere. Detailed spatial and temporal data on extreme events will also be useful in detecting and diagnosing weather pattern anomalies that might be connected with short-term climate change.

GEM Cost Model. GEM technology readiness is currently at the phase-A level, with some subsystem development work yet necessary on the scanning/morphing subreflector, radiometer calibration, and momentum compensation subsystems. Pending laboratory demonstration of these systems GEM would be suitable for phase-C flight model development and subsequent flight on either the next upgraded series of operational GOES (e.g., GOES-R+, starting in ~2012) as an Instrument of Opportunity (IOO) or as a stand-alone free-flying sensor under, e.g., the NASA New Millennium Program. It would also be suitable for immediate contract development by the U.S. aerospace industry.

The development costs (in FY04 dollars) for flight models of the GEM sensor have been estimated by the GMSWG to be ~$35M non-recurring plus ~$32M per unit. This estimate excludes bus, launch, and operating costs. The cost structure, technical readiness, and anticipated benefits of GEM make it attractive as a potential candidate for a geosynchronous bridge mission prior to the launch of the first GOES R.

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