Applications of Geostationary Hyperspectral Infrared Sounder Observations
Progress, Challenges, and Future Perspectives

Jun Li, W. Paul Menzel, Timothy J. Schmit, and Johannes Schmetz

ABSTRACT: A hyperspectral infrared (IR) sounder from geostationary orbit provides nearly continuous measurements of atmospheric thermodynamic and dynamic information within a weather cube, specifically the atmospheric temperature, moisture, and wind information at different pressure levels that are critical for improving high-impact weather (HIW) nowcasting and numerical weather prediction (NWP). Geostationary hyperspectral IR sounders (GeoHIS) have been on board China’s Fengyun-4 series since 2016 and will be on board Europe’s Meteosat Third Generation (MTG) series in the 2024 time frame; the United States and other countries are also planning to include GeoHIS instruments on their next generation of geostationary weather satellites. Although availability of on-orbit GeoHIS data are limited currently, studies have been conducted and progress has been made on developing the applications of high-temporal-resolution GeoHIS observations. These include but are not limited to deriving three-dimensional wind fields for nowcasting and NWP applications, trending atmospheric instability for warning in preconvective environments, conducting impact studies with data from the experimental Geostationary Interferometric Infrared Sounder (GIIRS) on board Fengyun-4A, preparing observing system simulation experiments (OSSEs), and monitoring diurnal variation of atmospheric composition. This paper provides an overview of the current applications of GeoHIS, discusses the data processing challenges, and provides perspectives on future development. The purpose is to provide direction on utilization of the current and assist preparation for the upcoming GeoHIS observations for nowcasting, NWP and other applications.

KEYWORDS: Remote sensing; Satellite observations; Soundings

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The hyperspectral or high-spectral-resolution infrared (IR) sounders, or the advanced IR sounders (Menzel et al. 2018), such as the Atmospheric Infrared Sounder (AIRS) on the Earth Observing System Aqua platform, the Infrared Atmospheric Sounding Interferometer (IASI) on the MetOp series, the Cross-track Infrared Sounder (CrIS) on Suomi NPP (SNPP) and the Joint Polar Satellite System (JPSS) series, and the High-spectral Resolution Infrared Atmospheric Sounder (HIRAS/HIRAS-II) on Fengyun-3D/-3E, provide high-vertical-resolution atmospheric sounding information that can improve the forecast skill in numerical weather prediction (NWP) models. Together with microwave sounder and other measurements, hyperspectral IR sounder measurements have become important data sources for NWP; without hyperspectral IR sounders from polar orbit, the capability for forecasting high-impact weather (HIW) events such as tropical cyclones are significantly degraded (McNally et al. 2014). Measurements from hyperspectral IR sounders from polar-orbiting satellites are also valuable for nowcasting and forecasting other severe weather events (Li et al. 2011a,b; J. Li et al. 2012), understanding climate changes and variations (Hilton et al. 2012), and monitoring atmospheric environmental changes (Hilton et al. 2012; Clerbaux et al. 2009).

However, most of the applications for high-quality hyperspectral IR measurements developed to date are for those from sun synchronous orbits. Realizing such measurements in geostationary (GEO) orbits adds time continuity to the measurements and enables applications that can greatly enhance the current forecast capability, especially monitoring, nowcasting, and forecasting the rapid changing weather. Rapid changes in atmospheric thermodynamic and dynamic states are often associated with the occurrence of severe weather events; a GEO hyperspectral IR sounder (GeoHIS) can capture the atmospheric spatial and temporal variations of the preconvective environment, provide critical information for situation awareness, and enable better nowcasting. Moreover, assimilating that information into the NWP models would improve the HIW weather forecasts.

There is long history development of GEO-based sounding capability, starting from Visible Infrared Spin Scan Radiometer Atmospheric Sounder (VAS) in 1980 (Smith et al. 1981) and followed by GOES Sounder in 1994 (Menzel and Purdom 1994). While both the radiance measurements and products from VAS and GOES Sounder are useful for nowcasting and NWP-based applications, the sounding capability is very limited due to the limited number and spectral resolution of bands (e.g., 18 IR + 1 VIS for the GOES Sounder) (Menzel et al. 1998). “The VAS experience suggests that extension into the microwave region, and increased spectral resolution in the infrared region, are essential so that we can obtain soundings through persistent clouds and with improved vertical resolution. Geostationary microwave instruments and high-spectral-resolution infrared interferometers are feasible and would be highly useful” (Forward by Verner E. Suomi; Montgomery and Uccellini 1985). In addition, the spatial resolution of 10 km, temporal resolution of 1 h, and continental United States (CONUS)-only coverage were also factors limiting the applications of the legacy GOES Sounder measurements. Placing hyperspectral IR sounders on board GEO weather satellites has been studied and found to be...
feasible and very desirable, both technologically and scientifically; for more details, please refer to the 2021 NOAA/NESDIS Technical Report on the value of advanced IR geo sounders (Adkins et al. 2021) and the Atmospheric Chemistry and Physics paper by Smith et al. (2009).

The WMO 2040 vision of an integrated global observing system includes hyperspectral IR sounders from GEO as well as polar orbit, capable of retrieving atmospheric temperature, humidity, and motion (by tracking cloud and water vapor features) along with determining rapidly evolving mesoscale features, sea/land surface temperature, cloud amount and cloud-top height/temperature, atmospheric composition (aerosols, ozone, greenhouse gases, trace gases). EUMETSAT will have advanced IR sounders (IRS) in GEO orbit in the 2024 time frame (Holmlund et al. 2021), Japan is planning a GEO IR sounder for their Himawari-8/9 follow-on (Bessho et al. 2021), China has launched an experimental advanced IR sounder [Geostationary Interferometric Infrared Sounder (GIIRS)/FY-4A] into GEO orbit in 2016 and an operational one (GIIRS/FY-4B) in 2021 (Yang et al. 2017). The United States is considering GeoHIS to be part of their GeoXO program to better observe high-temporal-resolution moisture and motion over North America and other regions (Schmit et al. 2009; Iturbide-Sanchez et al. 2022). Table 1 summarizes the key attributes of the current and near-future hyperspectral IR sounders.

The current and upcoming GeoHIS are GIIRS and IRS (see Fig. 1 for the spectral coverages), both are two-band designed sensors with an IR longwave band mainly measuring atmospheric temperature and a middle-wave band measuring atmospheric moisture.

Figure 2 shows the atmospheric temperature weighting functions (Jacobian functions) (left panel) for GIIRS LW (B1) channels, and the moisture weighting functions (right panel) for GIIRS MW (B2) channels with U.S. standard atmosphere. The weighting functions reflect the sensitivity of observations to atmospheric changes, or the information contained in the observations regarding atmospheric vertical distributions. There is good sensitivity (hence information content) to both temperature and moisture in troposphere, while there is limited

Table 1. Key attributes of LEO (AIRS, IASI, CrIS, and HIRAS-II) and GEO (GIIRS and IRS) advanced sounders, spectral coverage, spectral resolution, orbit, and operator.

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Spectral coverage</th>
<th>Spectral resolution (cm⁻¹)</th>
<th>Spatial resolution (km, nadir)</th>
<th>Temporal resolution</th>
<th>Orbit (platform)</th>
<th>Operator (launch time)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AIRS</td>
<td>LW: 649–1,136 cm⁻¹ (15.4–8.80 μm)</td>
<td>0.55</td>
<td>13.5</td>
<td>Twice per day</td>
<td>LEO (PM) (Aqua)</td>
<td>NASA (4 May 2002)</td>
</tr>
<tr>
<td></td>
<td>MW: 1,212–1,612 cm⁻¹ (8.22–6.20 μm)</td>
<td>1.2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>SW: 2,169–2,673 cm⁻¹ (4.61–3.74 μm)</td>
<td>2.0</td>
<td></td>
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</tr>
<tr>
<td>IASI</td>
<td>LW: 640.2–1,210 cm⁻¹ (15.50–8.26 μm)</td>
<td>0.25</td>
<td>12</td>
<td>Twice per day</td>
<td>LEO (AM) (MetOp series)</td>
<td>EUMETSAT (first IASI: 27 Nov 2006)</td>
</tr>
<tr>
<td></td>
<td>MW: 1,210–1,100 cm⁻¹ (8.26–5.0 μm)</td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>CrIS</td>
<td>LW: 650–1,095 cm⁻¹ (15.38–9.13 μm)</td>
<td>0.625</td>
<td>14</td>
<td>Twice per day</td>
<td>LEO (PM) (Suomi NPP and JPSS series)</td>
<td>NOAA (first CrIS: 28 Oct 2011)</td>
</tr>
<tr>
<td></td>
<td>MW: 1,210–1,750 cm⁻¹ (8.26–5.71 μm)</td>
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<td></td>
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<td></td>
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</tr>
<tr>
<td></td>
<td>SW: 2,155–2,550 cm⁻¹ (4.64–3.92 μm)</td>
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<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>HIRAS-II</td>
<td>LW: 650–1,168.125 cm⁻¹ (15.38–8.56 μm)</td>
<td>0.525</td>
<td>14</td>
<td>Twice per day</td>
<td>LEO (EM) (Fengyun-3E)</td>
<td>CMA (4 Jul 2021)</td>
</tr>
<tr>
<td></td>
<td>MW: 1,168.75–1,920 cm⁻¹ (8.55–5.21 μm)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>SW: 1,920.625–2,550 cm⁻¹ (5.21–3.92 μm)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GIIRS</td>
<td>LW: 700–1,130 cm⁻¹ (14.28–8.85 μm)</td>
<td>0.625</td>
<td>16 (-A)</td>
<td>120 min for China region</td>
<td>GEO (Fengyun-4 series)</td>
<td>CMA (first GIIRS: 10 Dec 2016)</td>
</tr>
<tr>
<td></td>
<td>SW/MW: 1,650–2,250 cm⁻¹ (6.06–4.45 μm)</td>
<td>12 (-B)</td>
<td>30 min for local region</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IRS</td>
<td>LW: 680–1,210 cm⁻¹ (8.26–14.71 μm)</td>
<td>0.625</td>
<td>4</td>
<td>60 min for disc coverage</td>
<td>GEO (MTG-S)</td>
<td>EUMETSAT (~2024)</td>
</tr>
<tr>
<td></td>
<td>MW: 1,600–2,250 cm⁻¹ (4.44–6.25 μm)</td>
<td></td>
<td></td>
<td>30 min for Europe region</td>
<td></td>
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</tr>
</tbody>
</table>
information concerning atmospheric moisture in the upper troposphere. With such measurements from geostationary orbit, GeoHIS can capture the temporal variation of atmospheric temperature and moisture in the troposphere, which is very useful for situation awareness, weather nowcasting, and forecasting.

Fig. 1. IASI brightness temperature spectrum calculated from U.S. standard atmosphere along with the IRS (red) and GIIRS (green) spectral coverage. Beyond atmospheric temperature and moisture profiles, high-temporal-resolution atmospheric composites such as $O_3$, $NH_3$, and CO can also be measured.

Fig. 2. Atmospheric (left) temperature weighting functions (Jacobian functions) for GIIRS longwave band (B1) channels and (right) moisture weighting functions for GIIRS middle-wave band (B2) channels.
Although GeoHIS measurements are only available currently with limited coverage from an experimental satellite, studies on utilization of such new measurements have been conducted by the international satellite community for some time; this manuscript provides an overview of the applications of GeoHIS along with data processing challenges. The objective is to provide direction toward effective utilization of such measurements, when they become available, for nowcasting, NWP, and other applications. This overview of the GeoHIS capabilities for time continuous atmospheric thermodynamic, dynamic, and atmospheric composite information will hopefully be of interest to the science and user communities; it provides a quick summary on GeoHIS for the weather satellite community for better preparing the data utilization, as well as points to the direction of studies in the next a few years.

The second section overviews the current progress and status on the applications of GeoHIS data, the third section provides current approaches and further consideration for sounding the atmosphere from GeoHIS in cloudy skies, the fourth section outlines the challenges on the utilization of GeoHIS, and the fifth section discusses the future perspective and direction on the application of GeoHIS.

### Progress and status on the applications of GeoHIS

**Severe storm warning in preconvection and nowcasting applications.** A GeoHIS can provide hyperspectral IR radiances along with derived products at high temporal resolution (usually 5–30 min for a regional observation mode). The derived products include but are not limited to atmospheric temperature and moisture profiles, atmospheric instability indices, total precipitable water, three-dimensional (3D) atmospheric horizontal winds, and cloud-top properties. The atmospheric vertical profiles along with the instability indices provide critical information such as dryline, instability, and atmospheric lifting, in the preconvective environment for situation awareness. A regional observing system simulation experiment (OSSE) showed that a GeoHIS can provide instability information that follows closely to the nature run (representing truth) and provides indications hours before radar systems; but the legacy GOES Sounder or today’s advanced imagers such as the Advanced Baseline Imager (ABI) have limited capability for detecting the signals, due to the small number and spectral resolution of the IR bands available for sounding the atmosphere (Li et al. 2011b). Atmospheric temperature and moisture profiles from AIRS measurements on single field-of-view (FOV) basis shows that local extremely high atmospheric instability can be detected hours ahead of the subsequent convection on the leading edge of a frontal system or storm genesis, and the extremely high atmospheric instability is associated with the local development of the severe thunderstorm in the following hours (J. Li et al. 2012). The sounding product is very useful for tracking the progression of the dryline, assessing the depth of moisture in the atmosphere, tracking moisture return, and differentiating the potential for severe versus nonsevere storms.

Although the GOES Sounder and ABI legacy atmospheric profile (LAP) products (Schmit et al. 2019) are limited, a forecast demonstration during the Hazardous Weather Testbed (HWT) spring experiments showed that such products help understanding of how the atmosphere has evolved to its current thermodynamic state through instability indices and three-layered precipitable water (LPW from 0.3 to 0.7, 0.7 to 0.9, and 0.9 to the surface in sigma vertical coordinates). It is found that analysis loops of those fields improved “somewhat” (i.e., ≥3 on a scale of 1–5) the situational awareness and helped to increase confidence in near-future atmospheric moisture and stability evolution (www.spc.noaa.gov/publications/line/goesrhwt.pdf) pointing toward likely locations of ongoing and newly developing convection. In addition, the instability and moisture gradients, maxima and minima, and trends in the legacy atmospheric profile (LAP) fields were found to be the most unique and useful nowcast information, rather than the absolute values themselves since it was often along the moisture/instability gradients and within the areas of increasing moisture/instability that
local convection consistently developed. For example, drylines are often associated with severe storm occurrence and these can be monitored with hyperspectral IR sounder data. Figure 3 shows a dryline over the U.S. High Plains that becomes the focus for convective development later in the day on 22 April 2022 (top right for the 1300 UTC convective outlook). The gradients of total precipitable water (TPW) fields from both gridded NOAA Unique Combined Atmospheric Processing System (NUCAPS) and roughly coincident GOES-16 ABI (https://soundingval.ssec.wisc.edu/imagery) can be seen in the zoomed-in version of the images (including an image showing NUCAPS sounding availability points). NUCAPS gives values in regions of clouds while ABI has a higher spatial resolution. A user might use both to take advantage of the strengths of both sensors. A benefit of future GeoHIS over NUCAPS is animation (although no microwave sensor is planned to be on the same platform with GeoHIS) and high spatial resolution (e.g., 4 km for IRS/MTG-S) which provide more retrieval coverage than the current hyperspectral IR sounders from polar-orbiting satellites.

High-resolution (horizontally, temporally, and vertically) observation-based information about near-future atmospheric moisture and stability changes is highly desired, and such information is only available from geostationary orbit. A survey of NWS forecasters during the 2016 HWT showed that most thought a cadence of 15 or 30 min would be ideal (www.goes-r.gov/users/docs/pg-activities/HWT2016_SE_GOESRPG_FinalReport.pdf). Since the future sounder will have high spatial resolution (e.g., 4 km for IRS on board MTG-S) (Holmlund et al. 2021), false RGB images based on IR channels can be generated for nowcasting applications. With GeoHIS, a principal component (PC)-based specific RGB can also be considered in monitoring, detection, and physical explanation of various atmospheric processes (Martinez and Calbet 2013). When combined with surface observations, and/or higher-spatial-resolution imager observations from the same geostationary platform, GeoHIS-based atmospheric temperature and moisture profiles can be improved in the boundary layer (Ma et al. 2021a), which is very useful for local monitoring of the evolution of atmospheric instability associated with local storm development. Figure 4 shows sounding examples from NUCAPS and NUCAPS + ABI, along with collocated RAOBs in clear and cloudy skies, respectively. ABI can
help NUCAPS at low levels, especially in cloudy skies; the clear measurements from a high-spatial-resolution imager can help GeoHIS soundings in partially cloud-filled footprints. With continuous soundings from GeoHIS, atmospheric thermodynamic structure changes can be monitored for improved nowcasting; for example, Maier and Knuteson (2021) found that the 2-h sampling interval of the GIIRS geostationary sounder was able to capture the transition (over 16 h) from a stable to an unstable atmosphere.

While temporal resolution is very important for nowcasting with GeoHIS, spatial resolution is also critical for detecting storm-favorable environments; cases studies (J. Li et al. 2012) have shown that higher-spatial-resolution sounding retrievals provide more useful warning information in the preconvective environments for determining favorable locations of convective initiation (CI) than coarser-spatial-resolution soundings. Di et al. (2021b) also show that the current hyperspectral IR sounders with 12–16-km spatial resolution at nadir have limited capability for delineating the small-scale atmospheric variations associated with local storm development, while future GeoHIS with 4–8-km spatial resolution at nadir can capture those variations. Regarding the temporal resolution, most forecasters need moisture information every 5–15 min (Schmit et al. 2019); higher temporal resolution provides even better retrieval products that include 3D horizontal winds (Ma et al. 2021b). With large volumes of data associated with GeoHIS, using PC-based information for nowcasting applications should be further investigated.

**Numerical weather prediction applications—Prelaunch OSSE studies on GeoHIS.** In the absence of observation data for impact studies, OSSEs for NWP (Hoffman and Atlas 2016) have been used to understand the added value of such new observations for both regional and global forecasts. OSSEs are sensitivity tests designed to answer questions of impact and value brought about by new observing systems, usually in numerical weather prediction models, in which a nature run (representing truth) from a free atmosphere is generated by a numerical model and then used to simulate the current and new observations, while in another independent model the data are assimilated to study the impact or added value of
the simulated future observing system. Traditional OSSEs are computationally expensive to run. Quick OSSEs and hybrid OSSEs are extensions of the traditional OSSEs. A quick OSSE is mainly used in high-resolution regional models for the evaluation of future observations to effectively reduce the computational complexity from traditional OSSEs and the associated uncertainty. Unlike the traditional OSSE, a hybrid OSSE does not use the free atmosphere in a nature run but instead a high-temporal- and high-spatial-resolution analysis or reanalysis data, such as the ERA5. This gives a hybrid OSSE two advantages over a traditional OSSE: 1) only future observations from high spatiotemporal resolution are simulated, while other existing observations are from actual measurements; 2) forecast results cannot only be verified with truth (analysis/reanalysis) used to simulate observations, but they can also be verified with actual independent in situ observations.

Over the past decade, there have been many OSSEs showing the importance of GeoHIS in weather forecasts, including global-, regional-, and storm-scale OSSEs. A global OSSE study by Bormann et al. (2019) shows the impact from a dearth of hyperspectral IR sounder measurements in low-latitude regions for NWP. Okamoto et al. (2020) studied the positive benefit from a GeoHIS on the next Himawari satellite in a hybrid OSSE in both global and regional NWP models; in a global hybrid OSSE they demonstrated that the GeoHIS clear-sky radiance assimilation leads to significant improvements in forecasts of the representative meteorological field and reduces tropical cyclone (TC) errors, while in a regional hybrid OSSE, the precipitation and atmospheric thermodynamic and dynamic fields were shown to be generally improved. The value of a GeoHIS for monitoring and forecasting heavy rainfall events from improved delineation of water vapor distribution and transportation were clearly demonstrated; these improvements of analysis and forecasts in both regional and global scales are believed to be due to frequent observations available for assimilation over a wide region of Japan and in the western Pacific. Figure 5 shows the zonal mean of the monthly averaged relative difference (%) between experiment (EXP) and control (CNT) for root-mean-square errors (RMSEs) verified against the Met Office (UKMO) model. A positive value indicates positive impact while a negative value means negative impact; overall positive impact is found from EXP when GeoHIS data are used on top of the current observing systems (CNT) in a global NWP data assimilation system using 4DVAR.

Li et al. (2018) used a regional quick OSSE to demonstrate the value-added impact of GeoHIS for local severe storm (LSS) forecasts, and they found that the unique value of GeoHIS, the
high temporal resolution, is more beneficial to the forecast. Wang et al. (2021) further studied the impact of GeoHIS for LSS forecast in a regional NWP model using hybrid OSSE; impact results from two typical LSS cases in 2018 and 2019 show that a GeoHIS provides improved analysis and forecasts for LSS when used together with data from the existing observing systems including in situ measurements. Further analysis shows that both dynamic and thermodynamic fields are improved, along with forecasts of temperature, humidity, precipitation, and wind patterns. The overall RMSE was reduced by 5%. While this value may seem small, it is calculated over the whole domain, which includes regions of less impact. When including GeoHIS information, an erroneous precipitation was correctly reduced from over 25 mm h\(^{-1}\) to near zero. Both results from quick OSSE and hybrid OSSE for LSS impact studies are consistent. It is a significant challenge to calibrate a traditional OSSE so that when it is used exclusively with existing observing systems, the resulting impact is comparable to those from actual observations. The hybrid OSSE avoids the problem of calibration through verification using a LEO-based hyperspectral IR sounder such as CrIS, for example, through comparison between impacts from assimilating actual CrIS and simulated CrIS observations, respectively. The hybrid OSSE is ideal for accessing the added value from GeoHIS.

Added value is also demonstrated in a high-resolution storm-scale NWP; Jones et al. (2017) tested the assimilation of thermodynamic information from GeoHIS, and their OSSE indicates that assimilating both temperature and humidity profiles derived from GeoHIS reduced midtropospheric mean and standard deviation of analysis and forecast errors over those from assimilating conventional observations alone. Compared with hourly assimilation, 15-min cycling generally produced the lowest errors while also generating the best 2–4-h updraft helicity forecasts of ongoing convection. More recently, Adkins et al. (2021) have shown that a GeoHIS has the potential to have the most influence for a 24-h forecast over the CONUS.

While OSSEs offer a valued approach for understanding the impacts of GeoHIS and preparing for the applications in NWP, limitations exist with respect to the assimilation of GeoHIS. They include the following: 1) the model and assimilation system might not be state-of-art, for example, in some regional OSSE, three-dimensional variational (3DVAR) approach is used for assimilation instead of 4DVAR, which might underestimate the impact, especially the benefit of high-temporal-resolution information; 2) the focus is on using thermodynamic information, but not the dynamic information; 3) most OSSEs only include clear-sky data, and thus, thermodynamic, dynamic, and hydrometer information are not well used; and 4) simulation of high spatial–temporal resolutions are limited by using a nature run or current reanalysis data. These limitations should be addressed in future OSSE studies.

**Numerical weather prediction applications using on-orbit experimental data.** The GIIRS on board the Chinese experimental geostationary satellite Fengyun-4A, the first of the second generation of Fengyun geostationary satellite series (Fengyun-4 series), is the first GeoHIS in geostationary orbit. Spectral coverage is achieved in two bands, the longwave IR (LWIR) band covers 700–1,130 cm\(^{-1}\) (or 8.85–14.29 μm) and the middle-wave IR (MWIR) covers 1,650–2,250 cm\(^{-1}\) (or 4.44–6.06 μm). The spatial resolution is 16 km at nadir for GIIRS/FY-4A. The experimental Fengyun-4A GIIRS in 2016 was followed by an operational GIIRS on Fengyun-4B that has improved spatial resolution of 12 km at nadir. For detailed information about GIIRS specifications and the observation modes, refer to Yang et al. (2017).

Radiometric and spectral calibration algorithms have been developed and updated; the new version of GIIRS level 1B radiances have been publicly available since January 2019. Spectral and radiometric accuracies of the measured spectra from the latest version 3.0 algorithm (Guo et al. 2021) show a performance of 10 ppm in both longwave (LW) and middle-wave (MW) bands with around 1 K for most uncontaminated channels within the LW band. However, nonlinearity correction of interferograms and spectral quality improvements, especially for
the MW band, await further improvement. To assess the spectral calibration accuracy of GIIRS, an efficient and accurate spectral shift estimation and correction algorithm called Iterative Spectral Shift Estimation and Correction (ISSEC) (Han et al. 2021) was developed to estimate the spectral shift of each detector based on CrIS and GIIRS simultaneous nadir overpasses (SNOs). The spectral accuracy of resampled GIIRS L1b radiances are improved with a spectral uncertainty less than 10 ppm for most of the detectors based on the long-term trend and diurnal variation of spectral shift, which is helpful for the assimilation of GIIRS observations in NWP models.

For assimilation of GIIRS measurements in NWP models, Yin et al. (2020) investigated the bias correction of GIIRS/Fengyun-4A and developed quality-control procedures for GIIRS longwave radiance measurements including subfootprint cloud detection based on collocated Advanced Geosynchronous Radiation Imager (AGRI) cloud products. After bias correction and control, the GIIRS LWIR radiances were operationally assimilated into Global/Regional Assimilation and Prediction Enhanced System (GRAPES) global 4DVAR system (now CMA-GFS 4DVAR assimilation system) and initial assessment indicates substantial added value for improving the prediction of high-impact weather events such as TCs and cold waves. They also found that biases for the LWIR channels depend on FOV and latitudinal distribution, and only upper-tropospheric channels have the diurnal variation of biases. Fengyun-4A GIIRS LWIR radiances have been operationally assimilated into the CMA-GFS system since 2019, evaluations indicate overall neutral to positive impact from anomaly correlation (ACC) for 500-hPa geopotential heights over East Asia, while positive impact was found on HIW forecasts of events like cold waves and typhoons (Han et al. 2019).

Assimilation of GeoHIS is now also being expanded from measurements in clear sky to measurements from partially cloud-filled footprints with help from collocated imager measurements (Li et al. 2022a). This follows Wang et al. (2017), who found that TC forecasts can be significantly improved if sufficient data are assimilated, especially the thermodynamic information over the data sensitive regions. For example, track forecasts showed large uncertainties from almost all the operational systems for Joaquin (2015) starting from 29 September to 1 October; this was partly due to insufficient assimilation of observations, especially in cloudy regions. When more soundings around the clouds were added the track forecast improved dramatically. Figure 6 shows the Hurricane Joaquin (2015) case study with the assimilation of CrIS cloud-cleared (cld-clr) radiances. GSI v3.3 is used as the data assimilation system, and WRF-ARW v 3.6.1 is used as the regional NWP model. The data assimilated in the model included the conventional data, AMSU-A on board NOAA-15, NOAA-18, NOAA-19, and MetOp-A, ATMS and CrIS data on board Suomi NPP. The benefits from the assimilation of more CrIS data were emphasized in Wang et al. (2017); they showed that assimilation of thermodynamic information in cloudy (and also the sensitive) areas would improve the track forecasts. The improvement of initial condition in the cloudy areas by the assimilation of GeoHIS based on the example of CrIS has been demonstrated. With GeoHIS, more thermodynamic information in sensitive regions is available for assimilation and improvement in HIW forecasts can be expected.

Although assimilation of GeoHIS radiances has progressed and shown promise, the current studies with Fengyun-4A GIIRS cannot fully reflect the value of a nominal GeoHIS on NWP. Both spectral and radiometric calibrations need further improvement, and temporal and spatial resolutions for nominal observations are limited. Nevertheless, GIIRS from experimental Fengyun-4A and the upcoming operational Fengyun-4B are very useful for understanding the data and exploring new and improved methodologies for better utilization of GeoHIS measurements.

New atmospheric products from GeoHIS with focus on diurnal variations. Almost all the products generated by LEO hyperspectral IR sounders can be produced by GeoHIS, plus
GeoHIS can generate estimates of the atmospheric motion at several levels. GeoHIS also has the unique advantage of being able to measure diurnal variation of atmospheric water vapor, clouds (e.g., cloud-top pressure, cloud optical thickness, and cloud microphysical properties), surface temperature and emissivity, aerosol, atmospheric composites, spectral LW radiances, and other variables. General circulation models (GCMs) for weather forecasts and climate simulations continue having difficulties in modeling the diurnal and subdiurnal precipitation, particularly over land. The issue is related to inappropriate representation of the processes that control subdiurnal phenomenon like convection, and phenomena with diurnal time scales, such as mesoscale systems (Xie et al. 2018). Products from GeoHIS measurements reflecting diurnal variations will provide for a better understanding of relevant

Fig. 6. (a) The “best track” from National Hurricane Center (NHC) (black line), the 120-h track forecast from the assimilation of CrIS radiance (blue line), and the 120-h track forecast from the assimilation of the additional CrIS cld-clr radiances (red line) from 1800 UTC 30 Sep 2015. (b) The Jacobian function of CrIS channel 130 (730.625 cm⁻¹). (c) The assimilated CrIS data coverage (green dots) for channel 130 from CrIS overlapped on GOES-15 imager channel at 11 μm (gray; unit: K) at 1800 UTC 30 Sep 2015 for Hurricane Joaquin (2015). (d) As in (c), but for the assimilated CrIS clear plus cld-clr data coverage (green dots).
aspects of the fast components of the hydrological cycle (convective processes). This in turn will improve modeling, and predicting the atmospheric diurnal processes associated with significant weather. As convective processes are shown to be important in climate modeling it is expected that improved physical insight will lead to better convective cloud parameterizations in climate models (Kendon et al. 2021).

One example is atmospheric ammonia (NH₃) which is a critical greenhouse gas. Until recently it could not be monitored rapidly from space. With GIIRS measurements, Clarisse et al. (2021) reported NH₃ measurements 10 times per day from the Fengyun-4A/GIIRS. They found that unprecedented temporal sampling with GIIRS can measure diurnal and nocturnal variations of NH₃ and that day–night differences are absent in winter but can reach a factor of 2–3 in warmer months. Figure 7 (from Clarisse et al. 2021) shows monthly NH₃ averages for each of the 10 GIIRS overpass times for the months of January, April, and July 2020. Significant diurnal variation is evident in different locations in different months. The results show promise for improving knowledge about lower-tropospheric conditions. The vertical profiles of NH₃ and the other atmospheric composites are a significant capability that can be realized with GeoHIS.

As with hyperspectral IR sounders from the polar-orbiting satellites, the atmospheric composites such as CO, O₃, NH₃, SO₂, and CH₄ can be retrieved with GeoHIS if the spectrum covers the absorption regions. But compared with the polar-orbiting hyperspectral IR sounders, GeoHIS has the unique capability of capturing the diurnal cycles of those atmospheric composites. An additional important atmospheric constituent is CO₂. Although there are strong CO₂ absorptions in the longwave 15-µm and shortwave 4.7-µm spectral regions, the radiance sensitivity to atmospheric CO₂ change (e.g., 3 ppmv) is much weaker than to atmospheric temperature change (e.g., 1 K). In addition, the radiance is more nonlinear to CO₂ than the temperature; therefore, separating atmospheric CO₂ and temperature is relatively difficult. Simultaneous retrieval of atmospheric CO₂ and temperature profiles is less likely unless the spectral resolution is very high (e.g., 0.1 cm⁻¹ or higher) and the radiometric and RTM accuracies are also very high compared to the current hyperspectral IR measurements. Therefore, the CO₂ is usually assumed to be known when assimilating radiances in NWP or retrieving atmospheric profiles from the radiance measurements. Deriving the diurnal changes in atmospheric CO₂ from hyperspectral IR sounder measurements remains a challenge.

Another important new product is 3D horizontal mapping of tropospheric motions; GeoHIS not only provides continuous observations of atmospheric thermodynamic information, but also provides continuous dynamic information critical for weather monitoring, warning, and forecasting. The atmospheric motion vectors (AMVs) based on the geostationary imager observations using cloud and moisture feature tracking techniques have been widely used in weather analysis and forecast. The same concept can be also applied to the thousands of channels measured by GeoHIS. Such an approach has been demonstrated with AIRS moisture profile retrievals (Santek et al. 2019); it was found that the profile retrieval uncertainty is the largest source of error in 3D horizontal wind retrieval and that the coarser temporal resolution and the drier air over the high-latitude regions introduce additional limitations. With high-temporal-resolution GeoHIS measurements, it is possible to derive 3D horizontal wind by either tracking the moisture features in the profile retrievals or tracking radiances directly. Height assignment remains the most important component in tracking features; tracking features in moisture retrieval fields has the advantage of accurate height assignment but again the retrieval uncertainty is the big error source. Ma et al. (2021b) demonstrated the possibility of 3D horizontal wind retrieval using the 15-min GIIRS data using a machine learning–based approach. Their results show that the temporal, spatial, and vertical distributions of horizontal wind fields are captured very well with 15-min GIIRS observations; the higher-temporal-resolution (e.g., 15 vs 30 min) data provide 3D winds with better accuracy. Moreover, with continuous retrievals of 3D winds, the GeoHIS can provide 4D horizontal
Fig. 7. Monthly NH3 averages for each of the 10 GIIRS overpass times for January, April, and July 2020 (from Clarisse et al. 2021).
wind fields, although the updraft velocity is not included in the retrieval. Compared with a broadband sensor like ABI, GeoHIS has much higher vertical resolution and it can provide AMVs at more atmospheric layers. For example, ABI can provide AMVs by tracking features in only three water vapor bands, which suggests AMVs at three thick atmospheric layers; GeoHIS can provide AMVs from tracking features in 100 to 1,000 channels which indicate motion at many more atmospheric layers and can create wind profiles (e.g., AMVs at different pressure levels). GeoHIS 3D horizontal winds can be achieved by tracking features either in radiances directly or in moisture retrievals at selected pressure levels. It should be noted that the AMVs here are from water vapor feature tracking. When tracking cloud features, both GeoHIS and ABI can be used to generate those AMVs (and ABI even offers a VIS band).

GeoHIS provides measurements with high temporal resolution that are important for monitoring and predicting the rapidly changing weather events. Figure 8 shows an example of hourly GIIRS longwave BT spectrum temporal variations from Fengyun-4A over 4 h at one location in the storm environment along with the only CrIS longwave BT spectrum available in these 4 h. The atmospheric temporal variation is clearly revealed in the GIIRS spectra, especially the cooling from 0400 to 0700 UTC reflected at the 750–850 cm\(^{-1}\) spectral region, while the CrIS polar-orbit-based hyperspectral IR measurements cannot capture such variation.

GeoHIS also offers a significant opportunity to monitor and estimate boundary layer moisture changes over the day and to capture the rapid changes associated with subsequent severe weather developments. Sieglaff et al. (2009) showed that the near-surface water vapor structure and changes can be monitored using the information contained in the rotational water vapor lines in the infrared window from 8 to 12 \(\mu\)m. This large number of weak water vapor lines with different absorption line strengths comprise a set of measurements that can

Fig. 8. (left) GIIRS channel 329 (~11 \(\mu\)m) BT image at 0500 UTC 10 Jul 2018 and (right) the GIIRS BT spectra (700–750, 750–800, and 800–850 cm\(^{-1}\), respectively) at one location (marked with a red star in the left panel) from 0300 to 0700 UTC along with CrIS longwave-band BT spectrum at 0448 UTC.
be used to see small-scale horizontal and as well as vertical variations in boundary layer moisture. This information will be most beneficial for nowcasting severe weather as well as for short-term NWP and will be a vital contribution toward achieving weather readiness.

**Sounding the atmosphere from GeoHIS under cloudy skies**

While a microwave sounder data will not be available from the same geostationary platform, sounding the atmosphere with GeoHIS has unique advantages nonetheless. GeoHIS sounding is limited by cloud presence, but GeoHIS offers spatial and temporal continuity that can help mitigate the gaps caused by cloud presence. Moreover in clouds, GeoHIS provides various cloud products at high temporal resolution. This section summarizes current approaches for handling clouds and also considers GeoHIS soundings in cloudy skies, with a focus on thermodynamic and dynamic profiles as well as cloud products.

**Cloud products from GeoHIS.** It has been demonstrated by polar-orbiting sounders that cloud optical, physical, and microphysical properties [including cloud optical thickness and emissivity, cloud-top pressure (CTP) and cloud-top height (CTH), cloud phase, and cloud particle size] can be well derived from hyperspectral IR radiance measurements, usually with known atmospheric temperature and moisture profiles (e.g., from a background atmosphere). A one-dimensional variational (1DVAR) algorithm for retrieving cloud properties from hyperspectral IR measurements is usually based on optimal estimation (OE) (Li et al. 2004, 2005; Kulawik et al. 2006; Eldering et al. 2008). For example, the cloud products from long-term EOS Aqua measurements are derived at AIRS full resolution and provide unique, decadal-scale, global coverage of cloud properties and their annual cycles and variability within the mesoscale and synoptic scales (Kahn et al. 2014). With GeoHIS measurements, the same algorithm can be applied to derive cloud properties (either GeoHIS alone or combined with an imager on board the same platform) with high temporal resolution; this will add understanding on the diurnal cycle and variation therein. Furthermore, high-temporal-resolution cloud products from GeoHIS will help to monitor rapidly changing HIW events, such as LSS that develop rapidly once initiated, and the associated cloud products (e.g., the increasing cloud-top height and changing particle size) that can provide good indicators of storm development and evolution. This is also important in TC rapid intensification (RI); the changes in both cloud-top height and cloud microphysical properties are very useful for determining the TC impact, as well as verifying the numerical models.

**Deriving atmospheric temperature and moisture profiles in cloudy skies.** Deriving atmospheric temperature and moisture soundings from GeoHIS measurements in cloudy scenes is challenging for IR sensors alone. But some algorithms have been developed for soundings under cloudy skies using hyperspectral IR measurements. In one approach, called dual regression (Smith et al. 2012), the empirical orthogonal function (EOF) regression is based on “clear trained” and “cloud trained” datasets; it can retrieve surface skin temperature, surface-emissivity EOF coefficients, carbon dioxide concentration, cloud-top altitude, effective cloud optical depth, and atmospheric temperature, moisture, and ozone profiles above the cloud and below thin or broken cloud. Another approach features simultaneous retrieval of cloud properties and thermodynamic profiles using OE methods. For example, Irion et al. (2018) used single-footprint AIRS radiance measurements to retrieve atmospheric temperature, water vapor, surface temperature, cloud-top temperature, effective cloud optical depth, and effective cloud particle radius simultaneously. OE method requires a priori information, which can be derived from imager data from the same platform; if the imager data are not available, a general 1DVAR method can be used to derive the cloud properties and atmospheric profiles using regression results as a first guess (Zhou et al. 2007). It should be noted
that an accurate RTM that can simulate observations under cloudy situations is critical for simultaneous retrieval of atmospheric profiles and cloud properties. In case of thick clouds, it is not possible to derive soundings down to the surface, but it is possible to get soundings down to the cloud top. These algorithms can also be applied to GeoHIS measurements. With high spatial and temporal resolution, GeoHIS offers more opportunity for soundings in clear skies. Simultaneous retrieval of atmospheric profiles and cloud properties will be improved since more retrievals will be possible and the quality control (QC) will also be enhanced.

**Deriving atmospheric 3D horizontal winds under cloudy skies.** Usually, 3D horizontal winds can be derived under clear skies by tracking moisture movement (e.g., either in retrieved moisture profiles or radiances directly from two or more consecutive times). A recent study (Li et al. 2022b) also indicated that the moisture tracked wind profiles can also be derived from measurements in partially cloud-filled footprints, which increases the wind retrieval yield especially when the footprint size is relatively large (e.g., 16 km for GIIRS on board FY-4A and 12 km for GIIRS on board FY-4B). The subfootprint cloudiness (fractional cloud coverage and cloud-top height) influences the retrieval accuracy; higher (lower) clouds have more (less) influence and thicker (thinner) clouds have more (less) influence on the wind product. If sounder subfootprint cloud information is available (e.g., from an imager on board the same GEO platform), noticeable improvement is realized in the 3D horizontal wind retrievals. Subfootprint cloud information also provides better QC for applications in weather nowcasting and forecasting.

In addition, high-spatial-resolution and high-temporal-resolution GeoHIS measurements can be used to track cloud features in selected channels with weighting functions peaking at different pressure levels, so that wind retrievals can be derived in both clear (water vapor tracked wind) and cloudy (cloud-tracked wind) skies giving the retrievals temporal and spatial continuity. It should be noted that wind profiles can be derived in clear skies (and partially cloud-filled footprints), while only one level AMVs can be derived from cloudy skies since the IR radiance cannot penetrate beyond the cloud when it is optically thick.

**Challenges on the applications of GeoHIS**

GEO hyperspectral IR sounders provide seamless temporal and spatial observations that offer great opportunities but also present challenges that need to be addressed. The following are some of the challenges posed by GeoHIS measurements:

**Handling the large volume of data.** The significantly increased volume of data pose difficulties in processing, distributing, and extracting information in a timely manner. Besides calibration, geolocation processing that need specific attention, other application related challenges are listed here. First, data processing and distribution to users for near-real-time applications must be considered; this involves technical solutions such as lossless data compression, distributing only selected representative channels (Di et al. 2021a), and/or PCs. Those selected channels or PCs should retain major information while significantly reducing the data volume. In addition, the observation operators used to derive the atmospheric state from the observations need to be accurate and efficient. While the current operators, such as RTTOV, have been fast and accurate for limited channel broadband observations, the Jacobian calculations needed for sounding retrieval and data assimilation using GeoHIS hyperspectral measurements are time consuming. PCRTM can partly overcome the latency issue for real-time applications, more efficient operators for accurate Jacobian calculations are highly desirable. A combination of traditional numerical approaches and analytical mathematical forms for Jacobians in both clear (Li et al. 1994) and cloudy (Li et al. 2017) skies can significantly reduce the computation time while retaining the calculation accuracy.
**Extracting the temporal information.** The unique GeoHIS advantage of high temporal resolution offers the challenge of how to extract and use the associated information. Beyond 4DVAR for radiance assimilation in NWP, time continuity can be used to extract quantitative information accurately and efficiently. While many retrieval algorithms used for LEO hyperspectral IR sounders can also be applied to the GeoHIS, there are limitations for real-time or near-real-time applications. For example, separating fast from slow changing parameters in GeoHIS retrievals can be very useful for improving accuracy and latency. For the IRS on board the MTG-S mission [with high spatial (4-km) and temporal (5–30-min) resolutions] using temporal continuity, one can separate fast-changing surface skin temperature and from slow-changing surface emissivity assuming that within a time window (e.g., 3 h) the surface skin temperature is variable while the surface emissivity is stable. This has been successfully demonstrated with GEO imager data (Li et al. 2011a). Similarly, one can separate fast-changing atmospheric moisture from slowly-changing temperature profiles using a 1-h time window. Using the temporal information in the retrieval not only improves the latency, but also the accuracy due to the better constraints of the ill-posed inverse problem.

**Handling CO₂ diurnal variations.** Atmospheric CO₂ has both seasonal and diurnal variations. Since the CO₂ variation has significant radiometric influence on radiance calculations, especially in the CO₂ absorption spectral regions, accounting for CO₂ diurnal variation in forward calculations is very important for sounding retrieval and data assimilation (Di et al. 2020). For applications, the radiative effects due to CO₂ changes can be treated as additional observation uncertainties in the atmospheric temperature profile retrieval and data assimilation, and the influence on the temperature profile retrieval and radiance assimilation can be partially reduced by using selected channels not sensitive to CO₂ changes. But this approach does not solve the problem of separating CO₂ and temperature retrievals. One possible approach is to use observations from multiple times (e.g., N times) and to assume that within this time window (e.g., 3 h) the CO₂ is constant while the temperature varies. This implies that the CO₂ is slowing changing compared to the temperature within this time window, so that observations from multiple times can be used to retrieve one CO₂ profile and N temperature profiles. This fast–slow separation concept has the advantage of constraining the solution by reducing the degrees of freedom, but it needs to be tested and demonstrated with high quality GeoHIS data when they become available.

**Finding synergy with LEO sounders for enhanced application.** LEO sounders provide frequent observations over high-latitude and polar regions, while GeoHIS provides high-temporal-resolution data over tropical and middle-latitude regions. Synergy of GEO/LEO sounders for global sounding systems is very important. But a fundamental problem is how to homogenize both radiance data and products from LEO/GEO hyperspectral IR sounders; it is not only important for weather applications but also for climate applications (Li et al. 2019). The homogenization needs to consider the radiometric, geometric, and spectral differences among the various hyperspectral IR sensors. Ideally, gridded level 1B and level 2 data from both GEO and LEO sounders should be available at the highest-possible spatial and temporal resolutions for various applications. Figure 9 shows an example of the seasonal mean of homogenized water vapor radiances (6.5-μm radiances) from five geostationary satellites in clear skies in (i) winter [December–February (DJF)] (ii) spring [March–May (MAM)] (iii) summer [June–August (JJA)] and (iv) autumn [September–November (SON)] in 2017. With GeoHIS on five international geostationary satellites, global homogenized hyperspectral radiances with high temporal resolution (e.g., hourly) could be available for model evaluation and climate studies; this would be a significant contribution.
Using such homogenized radiances, Xue et al. (2020a,b) evaluated different reanalysis datasets; they found that the six reanalysis datasets have an overall good agreement with observations for upper-troposphere water vapor (UTWV) but demonstrated a widespread wet bias of UTWV in all reanalysis that is more dominant in large-scale subsidence regions. Further analysis indicated that the reanalysis systems still have considerable difficulties in capturing the observed features of the diurnal variation in UTWV observed by GEO satellites. Further evaluation of moisture and its temporal changes associated with storm development in NWP models is still necessary, and GeoHIS observations will be the unique source for such evaluation.

**Using large angle data.** Due to limb effects, data with large viewing angles are difficult to use. This is partly due to the RTM difficulty in simulating the 3D and limb effects, especially when clouds exist in the footprint. The current suggested cutoff threshold is 65° for local zenith angle, which significantly reduces the data coverage (Adkins et al. 2021). Including more data farther out on the limb for quantitative applications creates the need for limb correction or more accurate simulation of radiances over large angles. In addition, viewing geometry corrections (parallax correction) should also be considered for some quantitative products such as cloud products where the difference between the viewing latitude–longitude and the actual physical location of a given footprint is significant.

**Future perspectives on the applications of GeoHIS**

While preparations for utilizing GeoHIS data should be focused on the big data challenges for quantitative applications, the following should also be considered:

**Better assimilation of GeoHIS.** Four-dimensional variational data assimilation is an important tool for taking advantage of temporal information from GeoHIS. However,
Yin et al. (2021) demonstrated that assimilation of 15-min-interval GIIRS data provides better TC forecasts than that of 30-min-interval GIIRS data, and 30-min-interval data assimilation is better than hourly interval data assimilation. This is an important step in understanding the benefit of temporal information from GeoHIS (Schmetz 2021), for example, using or assimilating gradient information in time (and space) directly might be useful and potentially a simplification for applications (experiments are ongoing at the Cooperative Institute for Meteorological Satellite Studies) (Z. Li 2021, personal communication). For better use of temporal information, current thinning strategies for assimilating GeoHIS radiances should be reexamined in order to take better advantage of high spatial–temporal resolutions. In addition, cycled ensemble and hybrid-data-assimilated techniques could be used to take advantage of high-temporal information. Considering the large volume of data, PC-based assimilation should be further investigated and evaluated; ECMWF has carried out some studies (www.ecmwf.int/en/elibrary/13888-direct-assimilation-pc-data-global-nwp; www.ecmwf.int/en/elibrary/13892-error-diagnostics-pc-scores-assimilation). While radiance assimilation is still the primary focus, assimilation of retrieved products should be also be investigated. The retrieval process offers a data compression advantage that converts radiances from all channels to atmospheric parameters, but the retrieval uncertainty needs to be well quantified for assimilation.

Another important aspect to assimilating temporal information is the 3D horizontal winds mentioned above. Including 3D horizontal wind assimilation can overcome the limitations associated with water vapor radiance assimilation in the current system. However, questions related to assimilation of both thermodynamic and dynamic information still need to be well understood. For example, what are the combined and individual impacts from radiance and 3D horizontal wind assimilation, respectively? When the water vapor radiances are well assimilated in a 4DVAR system, what is the added value from 3D horizontal winds since the winds are also derived from radiances? Both 3D horizontal wind and radiance assimilation are affected by observation bias and errors; therefore, their estimation for 3D horizontal wind retrievals as well as assimilation of 3D winds together with radiances is also important.

Expanding assimilation of thermodynamic and dynamic information into cloudy regions is very important for further forecast improvement, especially in the regions sensitive for tropical cyclone forecasts. Although assimilation of radiances in cloudy skies is challenging (Li et al. 2016), there has been progress in the development of an all-sky RTM and in the use of high-spatial-resolution data from an onboard imager that can be applied to GeoHIS assimilation (Li et al. 2022a). In addition to assimilation of thermodynamic and dynamic information under cloudy skies, including the hydrometric information in the assimilation can further improve the forecasts, especially for tropical cyclones according to a study by Meng et al. (2021). Cloud-affected GeoHIS GEO satellite observations can aid in NWP initialization and forecasting. While direct assimilation of all-sky GeoHIS IR and imager near-IR/VIS radiances from GEO satellite is difficult, alternatively there is promise in the combined assimilation of GeoHIS clear radiances and cloud liquid/ice water path (CWP) retrieved from GeoHIS (and the imager on board the same platform). During daytime, NIR/VIS data from imager can be used together with GeoHIS for CWP, while during nighttime, CWP can be derived from GeoHIS and imager IR measurements although the observation errors will be larger. The two types (thermodynamic and hydrometric) of observations are spatially complementary to each other. There are three items to note for combined assimilation. 1) The CWP retrieval algorithm needs to include GeoHIS (e.g., together with imager) to take advantage of high-spectral-resolution information (e.g., better information on phase discrimination). In addition, the retrieval errors need to be well quantified for assimilation application. 2) The CWP operator needs to be developed. If the hydrometers are control variables in the assimilation system, the operator is simple and CWP data can be assimilated directly with an operator. However, if the hydrometers are not
the control variables in the assimilation system, the operator has to link the CWP and the moisture profiles, which makes the assimilation of CWP indirect. 3) To better implement the combined assimilation, the sensitivities in the assimilation to different combinations of cloud microphysical parameterizations and dynamic CWP observation errors need to be studied and understood, since different combinations provide different hydrometeor background fields for the CWP assimilation, and the CWP dynamic observation error allows more cloud measurements to be kept for the assimilation with a more reasonable data weighting. Together, the dynamic information, thermodynamic information, and hydrometer information from GeoHIS along with other data can be used for assimilation; more studies are focusing on the effective use of these three types of information in the assimilation to maximize the benefit of GeoHIS.

**Synergistic use of imager data on board the same platform.** Placing the GeoHIS and an imager on the same GEO platform (or nearby platforms) will significantly benefit the applications. These benefits include but are not limited to (i) using the sounder for height assignment of imager-based AMVs (especially for thin clouds), (ii) using the imager for better sounder applications in cloudy skies (e.g., better cloud detection and characterization for radiance assimilation, better sounding and cloud products; Li et al. 2004, 2005), and (iii) enabling sounder and imager intercalibration and comparison for better quantitative applications. Not only can the collocated imager cloud information help the sounder subfootprint cloud characterization for better assimilation (Wang et al. 2014), but also the imager-based cloud clearing can be applied to GeoHIS footprints with partial cloud cover and enable derivation of clear equivalent hyperspectral IR radiances. Such methodologies have been proven to be effective for assimilating the thermodynamic information from AIRS, CrIS, and GIIRS in partly cloudy regions and for improving the prediction of HIW events such as TCs (Wang et al. 2015, 2017; Li et al. 2022a). More importantly, IR sounder, imager, and lightning mapper together on the same GEO platform enable integrated observing of the whole process associated with high-impact weather events. In this scenario, having more overlap spectral regions between imager and sounder becomes even more important.

Products can also be improved with synergistic use of data of imager and sounder from the same platform. Those products include but are not limited to temperature and moisture soundings (Ma et al. 2021a), cloud-top and cloud-base heights, surface skin temperature and emissivity, and hurricane position and intensity. Taking advantage of high-spatial-resolution imager and high spectral resolution of sounder data for improving quantitative products deserves more attention and investigation.

**Model evaluation with focus on diurnal variation.** Due to thinning, cycling, and channel selection approaches, the data used for assimilation in NWP models are very limited; therefore, the high-spatial- and high-temporal-resolution GeoHIS data are still independent unique sources for evaluating the performance of different NWP models and reanalysis datasets. Compared with the GEO imager (e.g., AHI) data that are used for evaluating and comparing different forecast models (Jiang et al. 2020), GeoHIS water vapor information with more vertical layers will offer the opportunity for improved evaluation of model performance in the whole troposphere associated with most significant weather events. Beyond the use of radiances directly for model evaluation, the products such as cloud properties can also be used together with radiances for model evaluation, even for forecast product correction (e.g., using machine learning technique). For example, much more accurate cloud-top heights from GeoHIS are very useful for evaluating how well a NWP model can simulate the whole process of LSS from initiation to decay, or a TC from genesis to dissipation, especially during rapid intensification.
**New products exhibiting diurnal variation.** GeoHIS can provide atmospheric temperature, moisture, and composition of gases, as well as cloud properties that exhibit significant diurnal variations. Another important product is the hourly emissivity spectra; current hyperspectral emissivity is a monthly product developed at University of Wisconsin–Madison (Feltz et al. 2018). However, hourly emissivity spectra that define the diurnal variation would be very useful for improving longwave radiation calculations in numerical models (Jin and Liang 2006). The diurnal variation of surface emissivity was first revealed by Z. Li et al. (2012) using Spinning Enhanced Visible and Infrared Imager (SEVIRI), and later was verified with ground-based measurements (Zhang et al. 2014). Compared to GEO imager measurements that can only provide emissivity at limited broad bands, GeoHIS measurements offer the opportunity for deriving hourly hyperspectral IR emissivity spectra using a physically based retrieval method (Li et al. 2007; Li and Li 2008).

In summary, GeoHIS provides added value and new information for nowcasting, NWP model-based forecasting, and climate studies. The high temporal resolution provides unique value for improving the monitoring, understanding, simulating, and predicting the diurnal variations that are missing or limited in current numerical models. Large volumes of measurements impose significant challenges on preprocessing (calibration, geolocation, etc.), data dissemination and distribution, information extraction and timely applications, data assimilation, etc. These must be addressed in such a way that information content and timeliness is not compromised. Future studies should be focused on better use of the high temporal resolution for both products and application, maximizing the value through application of combined thermodynamic, dynamic, and hydrometric information from GeoHIS, synergistic use of imager and sounder data if on board the same platform, and exploring the new products and applications with focus on diurnal information, mitigating the risk due to large volume of data while retaining the main information with low latency for applications.

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**Data availability statement.** The GIIRS data are available from the National Satellite Meteorological Center data share site (http://satellite.nsmc.org.cn/PortalSite/Data/DataView.aspx?currentculture=zh-CN).