

SATELLITE-BASED ATMOSPHERIC INFRARED SOUNDER DEVELOPMENT AND APPLICATIONS

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A history of the meteorological satellite-based atmospheric sounder development and applications is presented and discussed.

The accuracy of numerical weather prediction (NWP) depends on observations from a variety of sources, a high-performance computer system, and an advanced numerical model with data assimilation technology. Since over 70% of Earth's area is covered by water (oceans and inland waters) as well as mountains, deserts, and polar ice, it is impossible to realize traditional ground-based observations of the atmospheric state globally. Even for areas where

traditional observations are relatively dense, it is hard to satisfy the spatial and temporal requirements of mesoscale weather forecasts. In addition, information on atmospheric composition such as atmospheric ozone, dust, methane, sulfur dioxide, and carbon monoxide are often not measured in ground-based observation systems. The concept of using satellite infrared (IR) radiation measurements to retrieve atmospheric temperature was first proposed by King (1956). Kaplan (1959) noted that the radiation from different spectral regions comes from different atmospheric layers, which can be used to retrieve the atmospheric temperature at different heights. Wark (1961) proposed a satellite vertical sounding program to measure atmospheric temperature profiles. As meteorological satellites evolved from the *Television Infrared Observation Satellite-1 (TIROS-1)* in 1960 to include atmospheric sounding capabilities, advanced computers combined with better atmosphere radiative transfer theory opened the way to address important issues in weather forecasting and global climate change research. This included determining the initial conditions for NWP, the early warning and prediction of global weather processes and events, estimating the global radiation energy

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The abstract for this article can be found in this issue, following the table of contents.

DOI:10.1175/BAMS-D-16-0293.1

In final form 26 September 2017

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budget, monitoring global ocean conditions and ocean–atmosphere interactions, observing land and biosphere seasonal trends, evaluating the changes in atmospheric trace gases, monitoring global climate change, and many more. This paper provides an overview and discusses the development of satellite vertical sounding capability, quantitative retrieval theory, and applications of meteorological satellite-based sounder measurements, with a focus on infrared sounding.

DEVELOPMENT OF SATELLITE-BASED ATMOSPHERIC VERTICAL SOUNDING CAPABILITY.

Three-dimensional atmospheric temperature and moisture soundings from satellites rely on careful selection of spectral channels with different absorption characteristics within an atmospheric molecular absorption band. Strong absorption channels detect radiation from high in the atmosphere, while weak absorption channels detect radiation from low in the atmosphere plus Earth's surface. The carbon dioxide (CO_2) IR absorption bands, with CO_2 mixed almost uniformly in the air, can provide information on an atmospheric temperature profile for any given region of the globe; complementing this, the water vapor (H_2O) IR absorption bands can provide information regarding the atmospheric moisture profile. The first atmospheric sounding instrument was launched nearly 10 years after the first imaging instrument. In the data-sparse Southern Hemisphere, positive NWP impact was almost immediate (Kelly et al. 1978), while in the Northern Hemisphere, it was not realized for nearly another 10 years (Eyre 1997). Improved global impact was achieved in the mid-1990s when radiances rather than retrieved temperature/humidity profiles were assimilated in the NWP models (Eyre et al. 1993; Andersson et al. 1994); however, the full potential of these sounding data are still to be achieved.

Nimbus-3, carrying two of the world's first satellite sounders, was launched in April 1969 by the United States. One, the Infrared Interferometer Spectrometer (IRIS), measured radiation from 5.0 to $25\text{ }\mu\text{m}$ in roughly 320 narrow spectral channels within a field of view (FOV) of roughly 95 km using a modified Michelson interferometer. IRIS provided information on the vertical structure of atmospheric temperature, water vapor, and ozone and the emissive properties of Earth's surface and demonstrated that measurement of Earth-emitted spectra of good quality (with precision within 1%) was possible (Hanel et al. 1970). The other, the Satellite Infrared Spectrophotometer (SIRS)-A, made complementary measurements in

seven comparatively broad spectral channels in the carbon dioxide band (12–15 μm) and one spectral channel in the atmospheric window centered at 11.1 μm . With limited spectral selection, SIRS-A soundings offered coarse vertical resolution; furthermore, with a large instantaneous FOV of 250 km at nadir, approximately 90% of the measurements had interference from clouds limiting the coverage from clear-sky soundings. Nevertheless, SIRS-A soundings improved the weather analysis–forecasting operations at that time (Smith et al. 1970). Between 1970 and 1978, atmospheric temperature and moisture profile sounding instruments evolved in a series of flight experiments conducted on several *Nimbus* polar-orbiting satellites.

Meanwhile, Professor Verner Suomi from the University of Wisconsin–Madison proposed the idea of atmospheric sounding from a geostationary Earth-orbiting (GEO) satellite that was realized in 1980 on the U.S. *Geostationary Operational Environmental Satellite-4* (GOES-4). The first Visible and Infrared Spin Scan Radiometer (VISSR) Atmospheric Sounder (VAS; Smith et al. 1981; Hayden 1988) accomplished high-temporal-frequency sounding of Earth's atmosphere from more than 30,000 km above the equator. VAS had 12 sounding channels from 4 to $15\text{ }\mu\text{m}$ in and in between the carbon dioxide and water vapor absorption bands with a spatial resolution of 7 or 14 km at nadir; VAS also had one visible channel with 1-km horizontal resolution at nadir for cloud detection. With observations every hour (or better) over the same area, the GEO sounder has the potential for observing the short-term finescale characteristics of atmospheric temperature and moisture associated with convection. However, VAS had limited vertical resolution and limited spatial coverage as it needed multiple sampling to get a high signal-to-noise ratio (SNR); this restricted the potential for observations of sudden strong vertical changes in atmospheric temperature and moisture associated with convective storm environments.

In the late 1990s, direct assimilation of satellite sounder radiances (not the derived profiles) in global NWP models provided the impetus to achieve forecast improvement in the radiosonde-rich Northern Hemisphere, bringing positive impact in both hemispheres (the radiosonde-poor Southern Hemisphere had benefitted immediately from the satellite soundings; Kelly et al. 1978). Improving NWP accuracy by using satellite soundings became a focus for many operational (op) NWP centers around the world. Advances in atmospheric sounding technology enabled broader spatial coverage as

nadir-only observations gave way to cross-track scanning measurements of wide swaths and the gradual improvement in spectral resolution, spatial resolution, and radiometric accuracy (see Table 1; Hayden 1971; Gavaghan 1998; Conway 2008; Ohring 1979; Smith et al. 1979; Menzel and Purdom 1994; Dong et al. 2009; Yang et al. 2012) from SIRS-A on *Nimbus-3* in 1969. Filter radiometers that possessed relatively high spatial resolution and broadband spectral resolution were placed on meteorological satellites in polar orbit [such as the National Oceanic and Atmospheric Administration (NOAA) and *FengYun-3* series] and GEO (such as the GOES series). Experimental trials were transformed into operational applications. The following paragraphs summarize the atmospheric sounding systems at three main development stages for the polar-orbiting operational meteorological satellites.

The first development stage (1972–78) featured the Vertical Temperature Profile Radiometer (VTPR) on the Improved TIROS Operational System (ITOS) satellite series, whose technical specifications were the same as SIRS-A. In the second stage (1978–98), the TIROS Operational Vertical Sounder (TOVS; Smith et al. 1979) on *TIROS-N* and *NOAA-6* to *NOAA-14* made measurements in 27 spectral channels with cross-track scanning coverage accomplished by the High Resolution Infrared Radiation Sounder (HIRS)/2, the Microwave Sounding Unit (MSU), and the Stratospheric Sounding Unit (SSU). HIRS/2 had 19 IR channels, covering the 15- μm carbon dioxide IR longwave (LW) absorption band, 4.3- μm carbon dioxide IR shortwave (SW) absorption band, and 6.7- μm water vapor (WV) absorption band as well as the 0.47- μm visible band; its spectral resolution was 3–60 cm^{-1} and spatial resolution was 17 km at nadir. MSU had four spectral channels in the 5-mm (60 GHz) oxygen absorption band with a spatial resolution of 103 km at nadir. SSU featured three spectral channels with a spatial resolution of 147 km at nadir; it was used to derive atmospheric temperatures in the stratosphere. The performance of the TOVS sounding system improved significantly over that of the VTPR. The increase in water vapor, SW IR, and stratospheric sounding channels provided the information content for deriving atmospheric water vapor profiles and improving the accuracy of lower-troposphere and stratosphere temperature profiles. Microwave sounders capable of penetrating clouds improved the atmospheric temperature sounding performance in cloudy regions. The TOVS system, with high-quality radiance observations, represented the transformation from limited accuracy

remote sensing to quantitative high-accuracy passive remote sensing of meteorological and hydrological parameters. Global multispectral infrared and microwave radiances, indicative of temperature and moisture profiles, have been available for operational weather forecasts ever since. The third stage (1998–2012) was realized with the Advanced TOVS (ATOVS; Li et al. 2000; English et al. 2000) on the *NOAA-15* to *NOAA-19* series, which introduced three instruments measuring radiances in a total of 40 spectral channels. The Advanced Microwave Sounding Units (AMSU) have AMSU-A and AMSU-B. AMSU-A has 15 channels, 13 in the 60-GHz oxygen absorption band for atmospheric temperature vertical distribution sounding from Earth's surface to 45 km (about 3-hPa atmospheric pressure layer) and 2 in the low-frequency channels (23.8 and 31.4 GHz) for atmospheric water phase determinations with a spatial resolution of 50 km at nadir. AMSU-B with five channels has three in the 183-GHz water vapor strong absorption lines to obtain the layered atmospheric water vapor information and another two at 89 and 150 GHz for determination of Earth surface characteristics with a spatial resolution of 16 km at nadir. The HIRS/3 and HIRS/4 are advanced versions of HIRS/2, which improved the sounding performance of five channels in the water vapor absorption and SW IR bands as well as increased the spatial resolution by a factor of 2. The defining characteristic of ATOVS was the significant improvement in microwave sounding, which improved the vertical resolution and retrieval accuracy for atmospheric temperature and moisture profiles. ATOVS provided global atmospheric soundings in all weather conditions (Li et al. 2000). Some of the ATOVS instruments are still in use.

A complementary emerging atmospheric sounding technology is found in radio occultation (RO). Signals transmitted by global positioning system (GPS) satellites and related constellations of navigation satellites are also proving to be powerful tools for advancing Earth system science. Each of these is part of the Global Navigation Satellite System (GNSS). The GNSS receiver records the amplitude and phase in terms of time, which are affected by the density of the air and the amount of moisture within it—more moisture or higher density lengthens the transmission time. Upper-tropospheric to lower-stratospheric temperature profiles and lower-tropospheric humidity profiles can be precisely obtained.

Atmospheric sounding using the RO technique was proposed by Fishbach (1965), Lusignan et al. (1969), and Zeng (1974). The proposal to use GNSS

TABLE 1. Satellite-based low-spectral-resolution passive atmospheric sounding radiometers. DMSP = Defense Meteorological Satellite Program; ITPR = Infrared Temperature Profile Radiometer; NEMS = Nimbus-5 Satellite Microwave Spectrometer; SCAMS = Scanning Microwave Spectrometer; SSM/T = Special Sensor Microwave Temperature Profiler; SSMIS = Special Sensor Microwave Imager/Sounder; MWTS = Microwave Temperature Sounder; MWHS = Microwave Humidity Sounder.

Launch year	Spacecraft	Name of sounding instrument	Type of sounding instrument	No. of spectral channels	Spectral range (spectral resolution)	FOV (at nadir)	Scanning domain (covering width)
1969	Nimbus-3	SIRS-A	Grating spectrometer	8	11–15 μm (5 cm^{-1})	250 km	Nadir orientation
		IRIS-A	Michelson interferometer	240	5–25 μm (5 cm^{-1})	170 km	Nadir orientation
1970	Nimbus-4	SIRS-B	Grating spectrometer	14	11–35 μm (5 cm^{-1})	250 km	~1,000 km
		IRIS-D	Michelson interferometer	393	6.2–25 μm (2.8 cm^{-1})	100 km	Nadir orientation
1972–79	ITOS-D series	VTPR	Filter wheel radiometer	8	12–19 μm (15 cm^{-1})	55 km	1,364 km
1972	Nimbus-5	ITPR	Multidetector telescope radiometer	7	3.8–20 μm (15 cm^{-1})	30 km	1,566 km
		NEMS	Dicke-type radiometer	5	0.5–1.35 cm (220 MHz)	200 km	Nadir orientation
1975	Nimbus-6	HIRS/I	Filter wheel radiometer	17	0.6–15 μm (15 cm^{-1})	30 km	2,240 km
		SCAMS	Scanning Dicke-type radiometer	5	0.5–1.35 cm (220 MHz)	150 km	2,400 km
1978–98	TIROS-N series	HIRS/2	Filter wheel radiometer	20	0.6–15 μm (15 cm^{-1})	18 km	2,240 km
		MSU	Scanning multireceiver radiometer	4	0.5–0.6 cm (200 MHz)	110 km	2,348 km
1980–94	GOES-4–GOES-7	VAS	Filter wheel radiometer	13	0.6–15 μm (10–150 cm^{-1})	7–14 km	Full disk
1979–2017	DMSP F10–F15	SSM/T	Conical scanning radiometer	7	50 GHz	200 km	1,500 km

signals as a source for Earth measurements appeared in the late 1980s at the National Aeronautics and Space Administration (NASA) and elsewhere. The first practical application of this technique was in the GPS/Meteorology (GPS/Met) experiment (Anthes et al. 1997). Thereafter RO-based operations have been regularly carried out, with more planned for the near future.

The RO-based data are widely used in NWP, climate change studies, and space weather observations. Bending angle or refractivity profiles are being assimilated into NWP with positive impacts. The very limited bias associated with these data provides a strong baseline for operational NWP. As multidecadal datasets become established over time, RO will robustly observe long-term climate trends in the upper troposphere–lower stratosphere (UTLS).

DISADVANTAGES IN FIRST-GENERATION SATELLITE ATMOSPHERIC VERTICAL SOUNDING TECHNOLOGY.

A major issue when considering both the TOVS and ATOVS systems concerns the very broad weighting functions associated with their spectral channel measurements, which influence the vertical resolution. The low vertical resolution results from the broadband spectral resolution of HIRS and GOES sounder (Menzel and Purdom 1994; Menzel et al. 1998) at 10–40 cm^{-1} (or the corresponding spectral-resolving power $\lambda/\Delta\lambda$ at about 100, λ representing the central wavelength for a certain channel and $\Delta\lambda$ its spectral width). The spectral response width is 100 times larger than the individual atmospheric absorption lines, so the observed broadband radiation is the average of many absorption lines with various strengths. Therefore,

TABLE I. Continued.

Launch year	Spacecraft	Name of sounding instrument	Type of sounding instrument	No. of spectral channels	Spectral range (spectral resolution)	FOV (at nadir)	Scanning domain (covering width)
1994–present	GOES-8	Sounder	Filter wheel radiometer	19	3–15 μm (13–80 cm^{-1})	8 km	Full disk
1998–2010	Modified GOES	HIS	Optimum scanning interferometer	512	3.7–17 μm	10 km	Programmable
2003–present	DMSP F16–F19	SSMIS	Conical scanning radiometer	24	19.4–183 GHz	75, 37.5, and 12.5 km	1,700 km
1998–present	NOAA-15–NOAA-19	HIRS/3 HIRS/4	Filter wheel radiometer	20	0.6–15 μm (3–50 cm^{-1})	17 km (HIRS/3); 10 km (HIRS/4)	2,240 km
		AMSU-A AMSU-B	Dicke-type radiometer	15 5	23.8–57 GHz 89–183 GHz	50 km 16 km	2,343 km 2,200 km
2006–present	MetOp-A and MetOp-B	HIRS/4 AMSU-A MHS	Filter wheel radiometer Dicke-type radiometer Dicke-type radiometer	20 15 5	0.6–15 μm (3–50 cm^{-1}) 23.8–57 GHz 89–183 GHz	10 km 50 km 16 km	2,240 km 2,343 km 2,200 km
2008–14	FY-3A and FY-3B	IRAS MWTS MWHS	Filter wheel radiometer Scanning full power radiometer Scanning full power radiometer	26 4 5	0.6–15 μm (3–50 cm^{-1}) 50–57 GHz (180–400 MHz) 150–183 GHz (500–2,000 MHz)	17 km 50 km 15 km	2,250 km 2,250 km 2,700 km
2011–present	Suomi NPP	ATMS	Cross-track scanning radiometer	24	23.8–183 GHz	75, 32, and 16 km	2,200 km
2013–present	FY-3C	IRAS MWTS-II MWHS-II	Filter wheel radiometer Scanning full power radiometer Scanning full power radiometer	26 13 15	0.6–15 μm (3–50 cm^{-1}) 50–57 GHz (3–400 MHz) 89–183 GHz (20–2,000 MHz)	17 km 15 km 15 km	2,250 km 2,250 km 2,700 km

the satellite-observed broadband radiation comes from a relatively thick atmospheric layer and can only provide coarse information about the atmospheric structure, limiting the ability to observe the atmosphere's high-level (fine) vertical structure (Eyre 1989). A second issue arises as the broad CO₂ spectral bands often overlap with the absorption bands of other gases such as O₃ and H₂O, causing the weighting function to be affected by these other absorption gases. A third limitation is that the spectral response function of these broad bands is not accurately known; it is derived by calculating the spectral transmittances and reflectances of the contributing instrument components rather than measuring it for the whole optical system in vacuum. Finally, a

fourth problem is that clouds often interfere at these low spatial resolutions and introduce errors to the final retrieval results. These four issues are inherent to the TOVS, ATOVS, and GOES sounders. The IR spectral filter technology of these passive remote sensors constrains the number of sensor channels, their spatial resolution, and their sensitivity to objective information. Improvements have been sought through new IR remote sensing technology that can offer better IR spectral resolution; now the sensor can resolve individual spectral absorption lines so that the effects of O₃, H₂O, and other trace gases can be distinguished and narrower weighting functions can be achieved that improve the vertical resolution of the atmospheric sounding.

TABLE 2. Spectral parameters of current and planned satellite-based hyperspectral IR sounders.

Satellite	Sounder	Spectroscopic method	Spectral range cm^{-1} (μm)	Spectral resolution (cm^{-1})	Channel No.	Subpoint resolution (km)	Sensitivity (NEAT)	Scan width (km)
ADEOS	IMG	Interferometer	715–3,030 (3.3–15.0)	0.1	~60,000	8	0.1 K	827
EOS Aqua	AIRS	Grating	LW 649–1,136 (15.4–8.80)	0.55				
			MW 1,212–1,612 (8.22–6.2)	1.2	2,378	13	0.15–0.35 K (at 280 K)	1,650
			SW 2,169–2,673 (4.61–3.74)	2.0				
MetOp	IASI	Interferometer	LW 640.2–1,210 (15.5–8.26)					
			MW 1,210–2,100 (8.26–5.0)	0.25	8,460	12	0.2–0.35 K (at 280 K)	2,052
			SW 2,100–2,700 (5.0–3.62)					
Suomi NPP (and JPSS)	CrIS	Interferometer	LW 650–1,095 (15.38–9.13)	0.625				
			MW 1,210–1,750 (8.26–5.71)	1.25	1,385	14	0.1–0.5 K (at 250 K)	2,200
			SW 2,155–2,550 (4.64–3.92)	2.5				
FY-3	HIRAS	Interferometer	LW 667–1,136 (15.00–8.80)	0.625			0.15 K (at 250 K)	
			MW 1,210–1,750 (8.26–5.71)	1.25	1,343	16	0.2 K (at 250 K)	2,300
			SW 2,155–2,550 (4.64–3.92)	2.5			0.3 K (at 250 K)	
FY-4	GIIRS	Interferometer	LW 700–1,130 (14.28–8.85)	0.8 (trial) 0.625 (op)	912 (trial) 1,188 (op)	16 (trial) 8 (op)	0.3 K 0.1 K	Regional/ meso- and microscale
			SW/MW 1,650–2,250 (6.06–4.45)	1.6 (trial) 1.2 (op)				
MTG	IRS	Interferometer	LW 700–1,210 (14.28–8.26)	0.625	1,740	4	0.2 K (at 280 K)	Full disk
MW 1,600–2,175 (6.25–4.60)								

DEVELOPMENT OF SATELLITE-BASED HYPERSPECTRAL ATMOSPHERIC SOUNDING TECHNOLOGY. High-spectral-resolution or hyperspectral IR atmospheric soundings have been accomplished with interferometers and grating spectrometers. Table 1 shows that the United States began utilizing these two kinds of technologies to develop medium- and low-spectral-resolution instruments in the 1960s, with SIRS-A using a grating approach and IRIS-A using an interferometer, both on *Nimbus-3*. In the 1990s, several hyperspectral IR atmospheric sounding instruments were developed, including an airborne High-Resolution Interferometer

Sounder (HIS; Smith et al. 1987), the polar-orbiting Interferometric Monitor for Greenhouse Gases (IMG; Shimoda and Ogawa 2000), and the grating-based Atmospheric Infrared Sounder (AIRS; Chahine et al. 2006) on the polar-orbiting Earth Observing System (EOS). Two geostationary high-resolution interferometer sounders, the GOES High-Resolution Interferometer Sounder (GHIS; Smith et al. 1990) and Geostationary Imaging Fourier Transform Spectrometer (GIFTS; Smith et al. 2006) were developed as well but never flown.

More recently, the Infrared Atmospheric Sounder Interferometer (IASI; Lerner et al. 2002; Karagulian

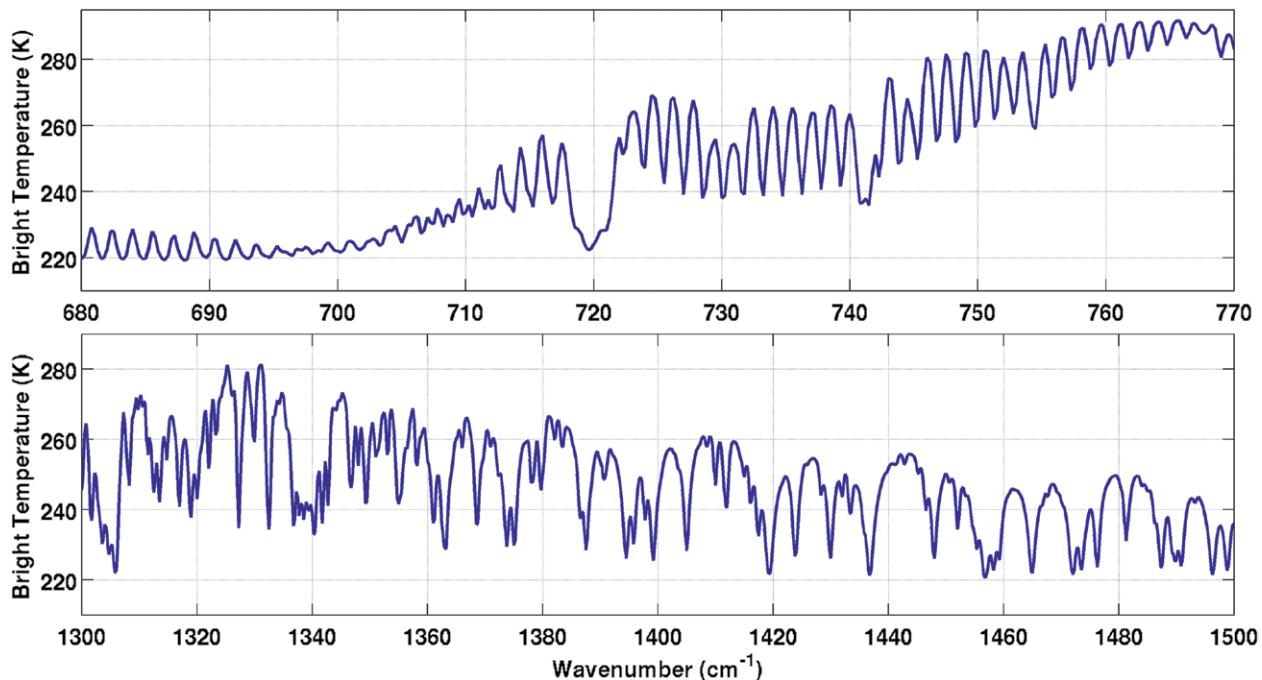


FIG. 1. Calculated IASI brightness temperatures in clear skies revealing the absorption lines of (top) the carbon dioxide band (from 680 to 770 cm^{-1}) and (bottom) the water vapor band (from $1,300$ to $1,500\text{ cm}^{-1}$) at high spectral resolution. U.S. Standard Atmosphere, 1976 with nadir view is assumed.

et al. 2010) has been flying on the European Meteorological Operational satellites (MetOp) series since 2006; the Cross-track Infrared Sounder (CrIS; Bloom 2001; Strow et al. 2013) was launched in 2011 on *Suomi National Polar-Orbiting Partnership* (*Suomi NPP*), which is the precursor for the next generation of U.S. operational Joint Polar Satellite System (JPSS); and the Hyperspectral Infrared Atmospheric Sounder (HIRAS) of China is being developed for China's next-generation polar-orbiting satellite series [*FengYun-3D* (*FY-3D*) and the follow-on]. In addition, China is flying the Geostationary Interferometric Infrared Sounder (GIIRS) on their GEO satellite series (*FY-4*; Yang et al. 2017), and Europe is planning the Infrared Sounder (IRS) for Meteosat Third Generation (www.eumetsat.int/website/home/Satellites/FutureSatellites/MeteosatThirdGeneration/index.html). Table 2 provides more details. The GEO hyperspectral IR sounders from China and Europe will enable virtually continuous atmospheric soundings (Schmit et al. 2009), which will provide unprecedented observations for weather forecasting and nowcasting (Li et al. 2011, 2012).

MAIN CHARACTERISTICS OF SATELLITE-BASED HYPERSPECTRAL IR ATMOSPHERIC SOUNDING SYSTEMS. When a sensor's spectral-resolving power ($R = \lambda/\Delta\lambda$) is higher than 1,000 and the observed radiation accuracy is better

than 0.2 K [noise equivalent temperature difference (NE Δ T)], it can provide almost monochromatic atmospheric IR observations of Earth and detail the spectral properties of CO_2 , H_2O , and O_3 as well as several trace gases. Spectroscopic evidence indicates that the three atoms of the CO_2 , H_2O , and O_3 molecules form a symmetrical array having three normal modes of vibration. The vibrational absorption within the IR is centered around 4.3 and $15.5\text{ }\mu\text{m}$ ($2,310$ and 660 cm^{-1}) for CO_2 , 6.7 and $12.7\text{ }\mu\text{m}$ ($1,540$ and 790 cm^{-1}) for H_2O , and $9.7\text{ }\mu\text{m}$ ($1,040\text{ cm}^{-1}$) for O_3 . More detailed features arise from the rotation of these molecules: for CO_2 , these lines are evenly spaced at 0.6 cm^{-1} around the 660 cm^{-1} vibrational line, while for H_2O , the line structure exhibits no clear-cut regularity and is distributed throughout the IR spectrum. Figure 1 shows the characteristic absorption lines caused by vibration and rotation of the CO_2 and H_2O molecules.

Figure 2 shows the weighting functions of the Chinese HIRAS (expected to be on board *FY-3D*, *FY-3E*, and *FY-3F*) and the low-spectral-resolution Infrared Atmospheric Sounder (IRAS; on board *FY-3A*, *FY-3B*, and *FY-3C*). Compared with IRAS, HIRAS has more detection channels, narrower $\Delta\lambda$ s, and more weighting functions. Higher spectral resolution and narrower weighting functions improve the sensitivity to a specific atmospheric vertical layer, which improves the sensor's vertical sounding

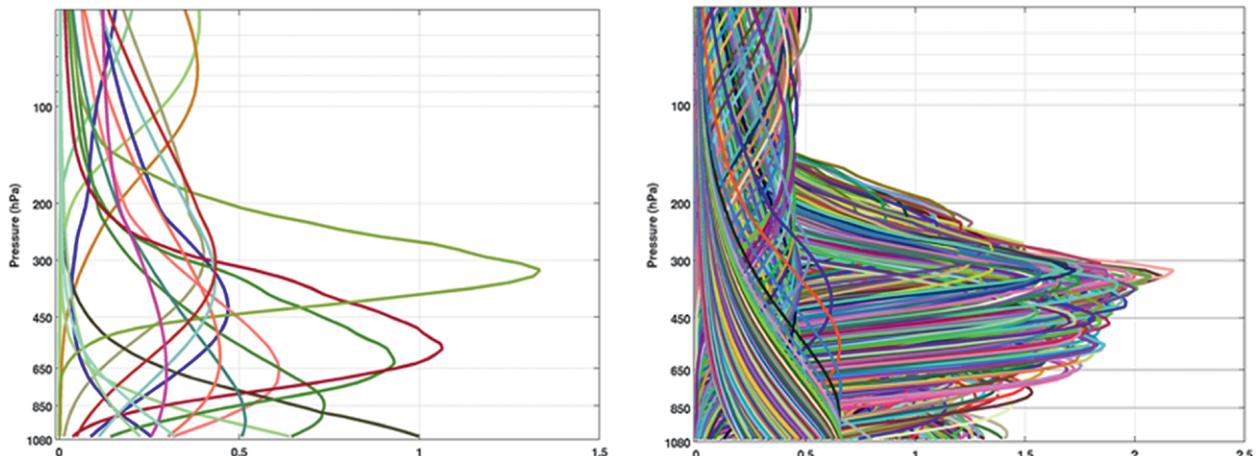


FIG. 2. Weighting functions of Chinese (right) hyperspectral infrared interferometry instrument HIRAS (FY-3D, FY-3E, and FY-3F) and (left) the low-spectral-resolution infrared spectrometer IRAS (FY-3A, FY-3B, and FY-3C). The horizontal axis represents the value of the weighting function; the vertical axis represents atmospheric pressure in units of hPa.

capability. Simulations by Zhang et al. (2005) and Wang et al. (2007) show that fine spectral resolution, accurate radiation measurements, good knowledge of the spectral response function (SRF), accurate spectral calibration, and a clear atmospheric path to the target, as well as uniformity in land surface emissivity, all contribute to defining the vertical resolution as well as the final accuracy of the atmospheric sounding.

After IRIS in 1969, the next high-spectral-resolution IR atmospheric sounder was IMG launched on *Advanced Earth Observing Satellite* (ADEOS) in August 1996 by the National Space Development Agency of Japan (NASDA). IMG was a very high-spectral-resolution (0.1 cm^{-1}) spectrometer covering $3.3\text{--}15 \mu\text{m}$, which enabled detection and monitoring of the spatial and vertical distribution of greenhouse gases such as CO_2 , CH_4 , O_3 , and H_2O . Unfortunately, ADEOS ceased operation in June 1997. There are currently four hyperspectral sounders in polar orbit. AIRS was launched on 4 May 2002 on board NASA EOS *Aqua*. AIRS has 2,378 channels in the IR range ($3.7\text{--}15.4 \mu\text{m}$; three absorption bands) with a spectral-resolution power ($\lambda/\Delta\lambda$) larger than 1,200, absolute radiation accuracy better than 0.2 K, cross-track scanning width of 2,650 km, and spatial resolution of 13 km at nadir. AIRS is designed to be used for deriving atmospheric temperature, humidity profiles, and total ozone. Research has shown that under clear skies, the retrieval accuracy and vertical resolution of AIRS can be up to 1 K and 1 km for temperature and about 15% and 2 km for humidity, respectively (Tobin et al. 2006b), using the AIRS science team algorithm (Susskind et al. 2003). Under cloudy skies,

AMSU-A and Humidity Sounder for Brazil (HSB), also on board EOS *Aqua*, were used together to improve atmospheric sounding. Overall, the best profile retrieval results were achieved from a combination of the IR and microwave radiance data that provided the maximum available thermal information, regardless of cloud conditions.

The first European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) polar-orbiting satellite, *Meteorological Operational-A* (*MetOp-A*), was launched on 19 October 2006 and carried the IASI based on Michelson interferometer and spectroscopic technology. The most significant characteristic of IASI is that it enables continuous observation of the atmosphere in the $3.62\text{--}15.5\text{-}\mu\text{m}$ spectral range. The spectral resolution of IASI is 0.25 cm^{-1} , and it has 8,640 channels with a spatial resolution of 12 km at nadir, cross-track scanning width of 2,052 km, and sample interval of 25 km. Another IASI followed on *MetOp-B* in 2011. To compare low-spectral to hyperspectral observations, *MetOp-A* and *MetOp-B* also carry the ATOVS atmospheric sounding system [HIRS/4, AMSU, and Microwave Humidity Sounder (MHS)]. IASI's continuous and hyperspectral observations can also be used to estimate other atmospheric constituents such as CO , N_2O , CH_4 , and SO_2 .

On 28 October 2011, the U.S. *NPP* satellite, later renamed *Suomi NPP* in honor of the distinguished pioneer of meteorological satellites Professor Verner E. Suomi, carried CrIS into space. *Suomi NPP* (SNPP) is the precursor of the new-generation JPSS series. CrIS replaces NOAA's legacy broadband IR sounder, the HIRS, which has been in operation

for nearly 40 years. CrIS is combined with the Advanced Technology Microwave Sounder (ATMS) for atmospheric sounding applications. CrIS has 1,305 channels covering from 3.92 to 15.38 μm with a nadir resolution of 14 km and cross-track scanning width of 2,200 km. The spectral resolution of CrIS is 0.625, 1.25, and 2.5 cm^{-1} , respectively, in the longwave, midwave (MW), and shortwave spectral bands, with option of providing observations with 0.625 cm^{-1} in all the spectral regions. ATMS replaces AMSU-A plus AMSU-B, with an increase in channels to 22 and swath width to 2,600 km.

China is developing its own hyperspectral IR atmospheric sounders: namely, HIRAS, planned to be carried on their polar-orbiting *FY-3D* (and the follow-ons), and GIIRS, launched on the first of their next-generation geostationary meteorological satellite *FengYun-4* (*FY-4*) series on 11 December 2016. The spectral range and performance of HIRAS is similar to CrIS, but the nadir spatial resolution is slightly lower. The spectral range of GIIRS is 4.4–14.2 μm , with slight differences between the experimental and operational satellites. The spectral resolutions for the experimental and operational satellites are 0.8 and 1.6 cm^{-1} for the longwave and 0.625 and 1.2 cm^{-1} for the midwave with nadir spatial resolutions of 16 and 8 km, respectively, both controllable for the sounding area. The IRS has been developed by Europe and is designed to fly on board EUMETSAT's next generation of three-axis stabilized GEO satellites, Meteosat Third Generation (MTG; Schmetz et al. 2012; Camps-Valls et al. 2012); it will provide atmospheric temperature and humidity profiles for a specific area with high temporal frequency and improved vertical resolution.

Figure 3 shows the spectral coverage of some recent and planned satellite hyperspectral sounders, and Table 2 shows their spectral properties. The solid line in Fig. 3 shows a typical brightness temperature spectrum from IASI, indicating the primary atmospheric absorption bands. Some of the prevalent uses of the

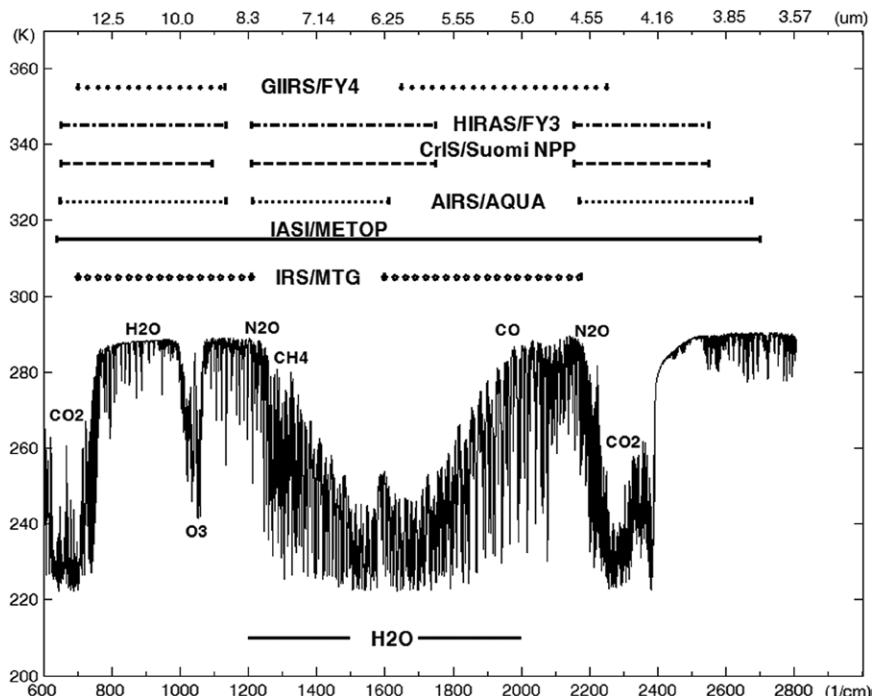


FIG. 3. Spectral coverage of several satellite-based hyperspectral IR sounders.

spectral ranges within the hyperspectral IR sounders are listed in Table 3. A hyperspectral sounder makes thousands of spectral channel measurements, which enable derivation of atmospheric vertical temperature and humidity profiles with improved accuracy compared with lower-spectral-resolution IR sounders. Studies have shown the positive influence of the sounder spectral resolution on the root-mean-square (rms) accuracy of the atmospheric profiles (with respect to radiosonde observations) when the other parameters of the sounder are unchanged [see Fig. 3 in Smith et al. (2009)].

TABLE 3. The primary uses of the different spectral ranges offered by a hyperspectral IR sounder.

Spectral range	Primary use
650–790 cm^{-1}	Atmospheric temperature and cloudy-sky retrieval based on the sensitivity to cold objects and CTH
790–1,180 cm^{-1}	Surface/cloud properties and ozone
1,210–1,650 cm^{-1}	Atmospheric water vapor and temperature; N_2O , CH_4 , and SO_2
2,100–2,150 cm^{-1}	Total column CO
2,150–2,250 cm^{-1}	Atmospheric temperature and total column N_2O
2,350–2,420 cm^{-1}	Atmospheric temperature
2,420–2,700 cm^{-1}	Surface/cloud properties

RETRIEVAL OF ATMOSPHERIC VERTICAL PROFILES FROM SOUNDER RADIANCE

MEASUREMENTS. As noted earlier, inference of atmospheric temperature and moisture profiles from satellite observations was first suggested in the 1950s. Now, after many years of theoretical research and operational practice, satellite sounding has evolved from statistical correlation approaches to quantitative physical and statistical retrieval of atmospheric profiles from radiances. Satellite IR remote sensing offers an indirect measurement of atmospheric temperature and moisture; radiances in different spectral channels or the path delays in a given FOV at a given time are the direct measurements made. A retrieval method is necessary to obtain the desired parameters such as the vertical distributions of atmosphere temperature and moisture; concentrations of absorbing gases like CO₂, O₃, and CH₄; and surface (land and ocean) plus cloud characteristics of any region on Earth.

The theoretical aspects for IR passive remote sensing of atmospheric and surface parameters include two parts. First, a model for radiative transfer through the atmosphere is needed to calculate the instrument's radiation measurements as a function of its spectral characteristics and Earth's atmospheric and surface state. This first part is called the forward model. Second, an inverse solution must be performed to retrieve the atmospheric and surface states from the radiation measurements. The forward model is mathematically well posed—for a given atmospheric state, there is one forward solution. However, the inverse solution, resulting in the retrieval of atmospheric and surface parameters from multispectral measurements, is mathematically ill posed—for any set of measurements, there are multiple solutions, and the optimal one must be selected.

In the forward model, or the radiative transfer equation, the upwelling radiance is dependent on the Planck function, the spectral transmittance, and the associated weighting function. The Planck function consists of temperature information, while the transmittance is associated with the absorption coefficient and density profile of the relevant absorbing gases. Obviously, the observed radiance contains the temperature and gaseous profiles of the atmosphere; therefore, the information content of the observed radiance from satellites must be physically related to the temperature field and absorbing gaseous concentration.

The radiative transfer equation (RTE) of a given spectral channel is a Fredholm integral equation of the first kind; the retrieval of atmospheric profiles

of temperature and moisture from a set of spectral channel measurements is unstable and nonunique. Since the 1970s, studies have been conducted on obtaining a stable solution. As noted by Rodgers (1976), the ill-posed inverse problem can be transformed into an estimation problem; by applying appropriate criteria to the inverse problem, the best solution can be obtained from all possible ones that are consistent with observations. Zeng's idea (1974) was essentially the same, but he called such a solution the statistically optimal one. Stabilization usually comes from inclusion of prior information (e.g., first-guess profiles). The atmospheric variation is retrieved for different vertical levels, for different vertical layers, or as a combination of continuous profiles—whichever representation is chosen to achieve an optimal estimate.

There are many models for the calculation of atmospheric transmittance, such as the line-by-line radiative transfer model (LBLRTM; Shephard et al. 2009). However, these accurate physical models are generally based on time-consuming line-by-line calculations and are not suitable for operational data processing. A rapid (or fast) calculation model for atmospheric transmission is necessary (McMillin and Fleming 1976). This approach is based on statistics: first calculating transmittances for a set of representative global atmospheric profiles via an accurate physical model, then establishing a statistical relationship between the calculated transmittances and the atmospheric parameters (e.g., temperature and moisture profiles). A fast model has a larger error than an accurate model; reducing the error of the fast model is still a challenge for sounder data applications, especially in cloudy situations. Fast models have been developed for research and applications; examples include the Community Radiative Transfer Model (CRTM; Han et al. 2006) and the Radiative Transfer for the TOVS (RTTOV; Eyre 1991; Saunders et al. 1999, 2017).

As indicated by the correlation between the measurements in many spectral channels, there are a limited number of independent pieces of information contained in a given set of channels. The 19 channels of the HIRS and the GOES Sounder contain only six independent pieces of information (Thepaut and Moll 1990; Schmit et al. 2009). An instrument with higher spectral resolution generally provides more independent pieces of information and channel selection out of the thousands available, which becomes important in order to reduce the computation load while maintaining the information content (Li and Huang 1994; Rodgers 2000, Rabier et al. 2002; Collard 2007; Ventress and Dudhia 2014).

Retrieval of atmospheric parameters from satellite sounding data is generally done with a statistical and/or a physical approach. The statistical regression method is based on the correlation between measurements from the spectral channels and the atmospheric parameters. The physical characteristics of the weighting function are not considered. As a result, the retrievals are less sensitive to the radiometric calibration, and the accuracy depends on the temporal and spatial representation of the statistical samples. Statistical regression cannot describe important nonlinearities between geophysical variables and radiances. However, it has advantages in efficiency and is usually applied in real-time or near-real-time processing. The physical–statistical retrieval method is based on solving the estimation problem; it involves radiative transfer calculations and inverse solutions and requires prior information of a statistical nature. Many methodologies have been proposed to solve this problem (Chahine 1970; Smith 1970; Zeng 1974; Rodgers 1976; Twomey et al. 1977; Smith et al. 1985; Fleming et al. 1986; Eyre 1989; McMillin 1991; Li et al. 1994; Li and Huang 1999; Ma et al. 1999; Li et al. 2000; Li and Huang 2001). Among those methodologies, the variational method to solve the estimation problem lays a foundation for retrieving atmospheric parameters from IR hyperspectral and microwave sounder measurements. To derive atmospheric soundings from hyperspectral IR sounder measurements via satellite data processing packages [e.g., International Moderate Resolution Imaging Spectroradiometer (MODIS)/AIRS Processing Package and Community Satellite Processing Package] for real-time and near-real-time applications, fast radiative transfer models mentioned above and efficient retrieval methodologies such as analytical Jacobian calculations (Zeng 1974) are important.

The physical retrieval method has made significant progress in clear and partly cloudy skies; however, in cloudy regions with measured radiances highly affected by absorption, scattering, and emission of clouds and aerosols, the estimation problem becomes more complicated. Exploring possible solutions that account for clouds and precipitation in the atmosphere remains a significant challenge (Li et al. 2016).

APPLICATIONS OF METEOROLOGICAL SATELLITE-BASED ATMOSPHERIC SOUNDER DATA. *Applications in numerical weather prediction.* With low instrument noise, thousands of channels, and hyperspectral resolution, instruments such as AIRS, IASI, and CrIS are able to

provide global information with high vertical resolution for NWP. The detail in the vertical profiles of the atmospheric state derived from hyperspectral IR sounders is unprecedented compared to that from the earlier sounders (Amato et al. 1997; Prunet et al. 1998). According to reports from a number of global NWP centers, hyperspectral IR sounders have the largest positive impact from a single instrument on the assimilation and prediction results of the current operational NWP systems. In combination with advanced microwave sounder data, AIRS and IASI data have been successfully assimilated at many operational NWP centers, such as the European Centre for Medium-Range Weather Forecasts (ECMWF; McNally et al. 2006; Collard and McNally 2009; Cardinali 2009; McNally et al. 2014), the National Centers for Environmental Prediction (NCEP; Le Marshall et al. 2005, 2006a,b), Météo-France (Auligné et al. 2003), the Met Office (UKMO; Cameron et al. 2005; Hilton et al. 2009; Joo et al. 2013), and the Japan Meteorological Agency (JMA; Okamoto et al. 2008), with significant positive effects. Assimilation of CrIS data has become operational at some NWP centers (Collard et al. 2012). Meanwhile, more observations from hyperspectral instruments have been used in some regional forecast models with positive impact on precipitation forecasts; examples include convective-scale models with a horizontal resolution of 1.5–2.5 km (Guidard et al. 2011) and prediction models for hurricane tracking (Li and Liu 2009; Liu and Li 2010; Xu et al. 2013; Wang et al. 2015; Zheng et al. 2015). As the NWP model vertical resolution continues to improve, the information from hyperspectral instruments is expected to become even more significant.

Sounder data assimilation in NWP started with retrieval assimilation in the 1980s, and positive or moderate impact was found in most NWP centers (Menzel and Chedin 1990); impact was more significant in the Southern Hemisphere than in the Northern Hemisphere, because of the scarcity of conventional observations in the Southern Hemisphere. The confinement to cloud-free or cloud-corrected infrared measurements reduced coverage and impact; complementary microwave measurements were used to extend coverage into nonprecipitating clouds. However, as NWP models advanced in the late 1980s, direct assimilation of radiances, from initial one-dimensional variational (1DVAR) to later three-dimensional variational (3DVAR) or four-dimensional variational (4DVAR), was adopted successfully by most NWP centers in the 1990s. Eyre (2008) provides a comprehensive overview on sounder data

assimilation, from retrieval to radiance assimilation, and theoretical aspects of radiance assimilation.

However, direct assimilation of radiances in NWP model leads to selection of a subset of the available hyperspectral data (usually hundreds of the thousands of spectral measurements) in order to balance computer resources needed against forecast benefits achieved. As a consequence, some signal-to-noise improvement is lost, and information content remains incomplete. The impact from using limited channel numbers in NWP (using an operational analysis technique) has been quantitatively documented (see, e.g., Le Marshall et al. 2006a,b, 2008). Overcoming the downside of channel subselection remains a challenge; studies underway include reverting to assimilation of sounding retrievals from advanced IR sounders, which have much higher vertical resolution than those from the low-spectral-resolution IR sounders, or using reconstructed radiances (computed from principal component scores). For example, in order to achieve consistency in vertical resolution between retrievals and model background, a method for correcting satellite profile retrievals for vertical-resolution-dependent biases has been formulated (Smith et al. 2015) for retrieval assimilation. Migliorini (2012) also pointed out that there is equivalence between radiance and retrieval assimilation under certain circumstances, and assimilation of transformed retrievals may be particularly advantageous for instruments with a very high number of channels. In recent years, the impact of retrievals on weather forecasting techniques, especially the impact of assimilating hyperspectral retrievals on forecasting of typhoon/hurricane tracks, has been researched (Zavodsky et al. 2007; Reale et al. 2008; Zheng et al. 2015). Using more channels, especially from the water vapor-sensitive part of the spectrum, is also currently under study.

Accounting for the effects of clouds is another important aspect in hyperspectral IR sounder data assimilation; difficulties arise in generating observation operators that describe cloud radiation accurately in the radiative transfer models. Errors arising when clouds are mistaken for clear sky or from observation data without an accurate description impede improvement in the assimilation analysis and produce insignificant improvement or even failure in the forecast (Wang et al. 2014). In most of the current operational systems, the observation operators of the radiative transfer in the assimilation have difficulty in simulating cloud-affected radiation accurately. The cloud descriptions in weather prediction models are usually not complete enough to provide quantitative

cloud water profile information; better identification, characterization, and utilization of cloud-affected radiances remain as major challenges for achieving practical quantitative applications.

Until recently, cloud-affected radiances were excluded, and only data from clear sky (clear FOVs and measurements from spectral channels not affected by clouds) were assimilated (Eresmaa 2014). This severely decreased the coverage and the information assimilated; for example, clear-sky data from AIRS account for only 10% of the total data (Huang and Smith 2004). To increase the amount of data assimilated, spectral channel measurements not seeing down to the clouds (McNally et al. 2006) or equivalent clear-sky brightness temperatures inferred from cloudy measurements were assimilated (Susskind et al. 2003; Li et al. 2005a; Le Marshall et al. 2008). In the former, the spectral channel measurements not seeing clouds were used to adjust and constrain the three- or four-dimensional propagation of atmospheric motions. In the latter, the cloud-cleared (or equivalent clear sky) IR sounder radiances for cloudy regions were estimated with additional information [either microwave sounders such as AMSU for AIRS/IASI and ATMS for CrIS or imagers such as MODIS for AIRS, the Advanced Very High Resolution Radiometer (AVHRR) for IASI, and the Visible Infrared Imaging Radiometer Suite (VIIRS) for CrIS]. Assimilation of cloud-cleared radiances has been found to improve the accuracy of tropical storm-track forecasts (Wang et al. 2015).

All-sky IR radiance assimilation has been difficult because 1) both NWP and radiative transfer (RT) calculations have larger uncertainties in cloudy regions, 2) satellite observations and NWP may not agree on the presence of clouds (e.g., the satellite sees clouds, but NWP does not and vice versa), and 3) atmospheric parameters have a higher nonlinear dependence on IR radiances in cloudy situations (Li et al. 2016). Based on the simplified concept of a single-layer black cloud, Pavelin et al. (2008) have implemented direct cloudy radiance assimilation based on cloud-top pressure (CTP) and effective cloud amount (ECA), estimated in the preprocessing through 1DVAR (Eyre and Menzel 1989; Li et al. 2001, 2004), to constrain the assimilation of cloud-affected infrared sounder channels in 4DVAR. In a similar vein, McNally (2009) has introduced an operational analysis scheme using cloud-affected radiances to good effect by extending the 4DVAR analysis control to include parameters that describe the cloud conditions and simultaneously to estimate these parameters together with temperature and humidity. Direct assimilation of all-sky

radiances is also being studied, with progress being realized for microwave humidity sounders (Baordo and Geer 2016; Guerbette et al. 2016). Lavanant et al. (2011) compared the results from different retrieval schemes for cloud parameters, finding consistency in those schemes. To better combine 1DVAR and 4DVAR, and optimize the parameterization of the microphysical process in NWP models using IR sounder observations through assimilation, one possible research direction thus becomes introducing the cloud microphysical process to 1DVAR. Studies show that the spatial distribution of precipitation forecasts can be improved significantly because 1DVAR can constrain the cloud microphysical process when combining 1DVAR and 4DVAR. With positive results reported by ECMWF, the Met Office, and some meteorological research institutes in the United States, cloudy hyperspectral IR data assimilation is beginning to show promise. A comprehensive analysis on cloudy data assimilation has been performed by Li et al. (2016).

Finally, it has been shown that the combined impact of hyperspectral IR and cloud-penetrating microwave systems exceeds the sum of their individual impacts in NWP (Liu et al. 2016). The data from the two systems are being assimilated into NWP systems, and optimal weighting of their respective information content continues to be studied.

Applications in severe weather warning. Overall, the satellite sounding information is benefiting weather forecasts, including severe weather warnings. Measurements by advanced IR sounders within the IR window region isolate many relatively weak water vapor and carbon dioxide absorption lines. The measurements in these absorption lines can provide key information for monitoring the evolution of the lower-tropospheric thermodynamic state (Sieglaff et al. 2009). In addition, the vertical profile information derived from the hyperspectral IR sounders can provide more abundant information important for severe storm nowcasting and short-term forecasting in the mesoscale environment; examples include the index related to stormburst, atmospheric stability, and the structure of the boundary layer (Li et al. 2011).

Sieglaff et al. (2009) proposed that the equivalent potential temperature differences between 800 and 600 hPa are indicative of thunderstorm potential. Li et al. (2011) found that AIRS is capable of depicting an unstable region (adding horizontal detail) in clear skies hours in advance of convection. Similarly, the atmospheric stability index derived from AIRS data

can also distinguish stable and unstable regions in the atmosphere, which is especially important for decreasing false alarms of severe convective storms. Furthermore, the track and intensity forecasts for typhoons/hurricanes can be improved when AIRS soundings at single field-of-view resolution are assimilated in a regional NWP (Li and Liu 2009; Liu and Li 2010; Wang et al. 2015).

The in-orbit suite of IASI, AIRS, and CrIS offers improved temporal and spatial coverage of hyperspectral IR remote sensing (Weisz et al. 2015). Combining these with other satellite data, ground station observations, and NWP analysis field data can improve the nowcasting of severe convective weather. Although the vertical resolution of current hyperspectral IR sounders has made a qualitative leap compared to previous sounders, the ability to capture convective potential is still limited by relatively low horizontal and temporal resolution. Hyperspectral IR remote sensing data with a higher temporal resolution, as from a geostationary satellite, will have significant advantages for making early warnings of severe weather events (Schmit et al. 2009; Li et al. 2011; Yang et al. 2017).

Applications in climate analysis. Factors affecting climate change (e.g., greenhouse gases and aerosols) and feedback mechanisms of moisture and clouds are receiving increased scrutiny. Hyperspectral IR instruments, such as AIRS, IASI, and CrIS, are becoming important data sources in these studies.

Upper-tropospheric water vapor (UTWV), an important greenhouse gas in the atmosphere, is contributing to global warming. However, its characterization in current reanalysis data and climate models is insufficient (Allan et al. 2003; Iacono et al. 2003; Solomon et al. 2010; MacKenzie et al. 2012). More recently, hyperspectral observation data from AIRS, IASI, and CrIS are being used for analyzing UTWV (Susskind et al. 2003; Liu et al. 2009; Divakarla et al. 2014). UTWV products from hyperspectral sounders have also been applied to the study of seasonal variance in monsoon regions (Gettelman et al. 2004), model assessment (Takahashi et al. 2016), and water vapor feedback mechanisms.

Clouds have a significant role in the energy balance and the hydrological cycle in the Earth–atmosphere system. However, there are large uncertainties in the cloud feedback mechanisms due to the various cloud types, complex structures, and nonisotropic radiance distribution, as well as the variety of cloud depictions in climate models (Sun et al. 2006; Williams and Webb 2009; Wu and Zhou 2011). Therefore, the

study of clouds remains an important component of climate change research, with satellite observations providing abundant cloud information. MODIS, GOES, and Multiangle Imaging SpectroRadiometer (MISR) have been making short-wavelength IR measurements of clouds along with *CloudSat* and *Cloud–Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO)* generating cloud profiles and cloud-phase information. The cloud-top heights inferred from the HIRS longwave CO₂ absorption band data have been used to determine the global high cloud distributions (Menzel et al. 2016). Furthermore, the hyperspectral IR sounder 12–15- μm spectral region is particularly sensitive to cloud-top height (CTH) and effective cloud cover, and the 9- μm band contains information on cloud optical thickness and particle size (Li et al. 2004, 2005b); these hyperspectral measurements have become the basis for joint retrievals of atmospheric and cloud parameters (Smith et al. 2012). Li et al. (2004, 2005b) used a 1DVAR approach with AIRS data to retrieve CTP, ECA, effective particle radius, and optical depth, with the latter two comparing favorably with the results from satellite- and ground-based active remote sensing instruments (Wu et al. 2005; Weisz et al. 2007). They also pointed out that AIRS cloud products have more abundant spectral features than MODIS cloud products, and the two can be complementary. Optimally the CTPs derived from advanced sounder data (e.g., from AIRS, IASI, and CrIS) are within 300-m precision, the cloud-top temperatures around 2 K, and the cloud coverages around 10% (August et al. 2012); but these numbers are cloud-state dependent (Eyre 1989). However, there are also some limitations; AIRS cloud microphysical parameters lack precision in thick clouds [cloud optical thickness (COT) > 10] and especially thin clouds (COT < 0.1) since IR observations have the largest sensitivity to the variations in clouds when the optical depth is between 0.4 and 4 (Huang et al. 2004; Li et al. 2005b; Weisz et al. 2007).

Strong absorption lines for CO₂ in the 4.3- and 15.3- μm IR bands have been used to obtain upper-atmospheric CO₂ distributions over several decades. The CO₂ content in the mid- and upper troposphere retrieved by combining AIRS with AMSU-A observations is consistent with aircraft and ground interferometer observations, for which the accuracy is around 2–3 ppmv (Crevoisier et al. 2004; Chahine et al. 2005; Strow and Hannon 2008). Based on a similar method, Crevoisier et al. (2009) calculated CO₂ data for one year with IASI and AMSU-A observations with an accuracy of about 3 ppmv. All the retrieval

products can be used to analyze the variance of CO₂ content, though these data records are not considered sufficiently long, as 20 years halves the 10-yr uncertainty of the trend (Wielicki et al. 2013). The global mean variability of CO₂ content is approximately 2 ppmv yr⁻¹ based on AIRS and IASI data (Strow and Hannon 2008; Crevoisier et al. 2009), and the total column quantity varies in concert with the baseline ground stations (Keeling et al. 1995).

Although AIRS, IASI, and CrIS are providing observations of high quality, the oldest of these, AIRS, has only operated for 15 years. Long-term climate trend analysis is premature. However, ultimately, more than 20 years of CrIS and IASI data will be available, with the anticipated continuous operation of MetOp and JPSS in the coming decades. Considering their long-term stability, the climate products of AIRS, IASI, and CrIS are expected to make significant contributions to global climate research.

Another important application relevant to climate studies involves the recalibration and validation of historical satellite data such as HIRS and AVHRR with data records of more than 40 years. With help of collocated hyperspectral IR sounder measurements, sensor-to-sensor differences in these long-term data records can be reduced. For example, HIRS measurements, made from 17 satellites since 1975, have been recalibrated using IASI. Uncertainties in the calibration of broadband radiance measurements [often attributed to inadequate knowledge of the SRFs as demonstrated by Tobin et al. (2006a)] have produced satellite-to-satellite biases in the HIRS data record. These biases have been reduced using an approach that starts by determining a linear model for the radiance changes in a specific spectral band in given atmospheric conditions due to SRF modifications (Chen et al. 2013). The hyperspectral measurements from IASI on *MetOp-A* satellite are used to simulate global HIRS observations and to determine the parameters in the linear models. The linear models are then used to estimate sensor-to-sensor corrections from measurements at simultaneous nadir overpasses (SNOs). In a related activity, hyperspectral IR sounder measurements have been and are being used to validate the broadband imager IR radiances on geostationary and polar-orbiting platforms through the Global Space-Based Inter-Calibration System (GSICS; <http://gsics.wmo.int/>), which is important for improving imager-based science products such as sea surface temperature (SST), land surface temperature (LST), and land surface emissivity (LSE), fire detection, etc., and their applications (Dash et al. 2010; Lu et al. 2016).

FUTURE PROSPECT OF SATELLITE-BASED ATMOSPHERIC SOUNDING.

Satellite-based three-dimensional atmospheric temperature and humidity profiles have been developing rapidly. The measurements have been widely applied in NWP, severe weather monitoring and warning, atmospheric environmental monitoring and forecasting, and climate monitoring and prediction. In the future, hyperspectral IR combined with advanced microwave measurements will provide improved three-dimensional structure of the atmosphere continuously over the globe. The FY-4A hyperspectral atmospheric sounder is the first of several planned missions to monitor the vertical structure of the atmosphere hourly and to capture the atmospheric motions in both horizontal and vertical directions ahead of high-impact weather events. With the development of advanced detectors on board CubeSats, such as NASA's Time-Resolved Observations of Precipitation structure and storm Intensity with a Constellation of Smallsats (TROPICS; <http://tropics.ll.mit.edu>) with a microwave sounder on board, it is foreseeable that CubeSats and similar technologies may also offer higher temporal resolution to global atmospheric sounding. There is the promise of further improvement in sounder application and impact.

ACKNOWLEDGMENTS. This work is supported by JPSS Risk Reduction and GYHY201406011. The authors wish to thank reviewers Dr. John Eyre and Dr. John Le-Marshall and editor Dr. Jeffrey Hawkins for their helpful insight and clarifications regarding the maturation of a satellite vertical sounding capability; we believe their efforts contributed significantly to a more comprehensive readable manuscript. Several figures and tables in this manuscript were created by Dr. Hui Liu and Dr. Wenguang Bai of National Satellite Meteorological Center (NSMC), CMA. The views and opinions expressed in this article are those of the authors and do not necessarily reflect the official policy of any agency of the U.S. government.

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