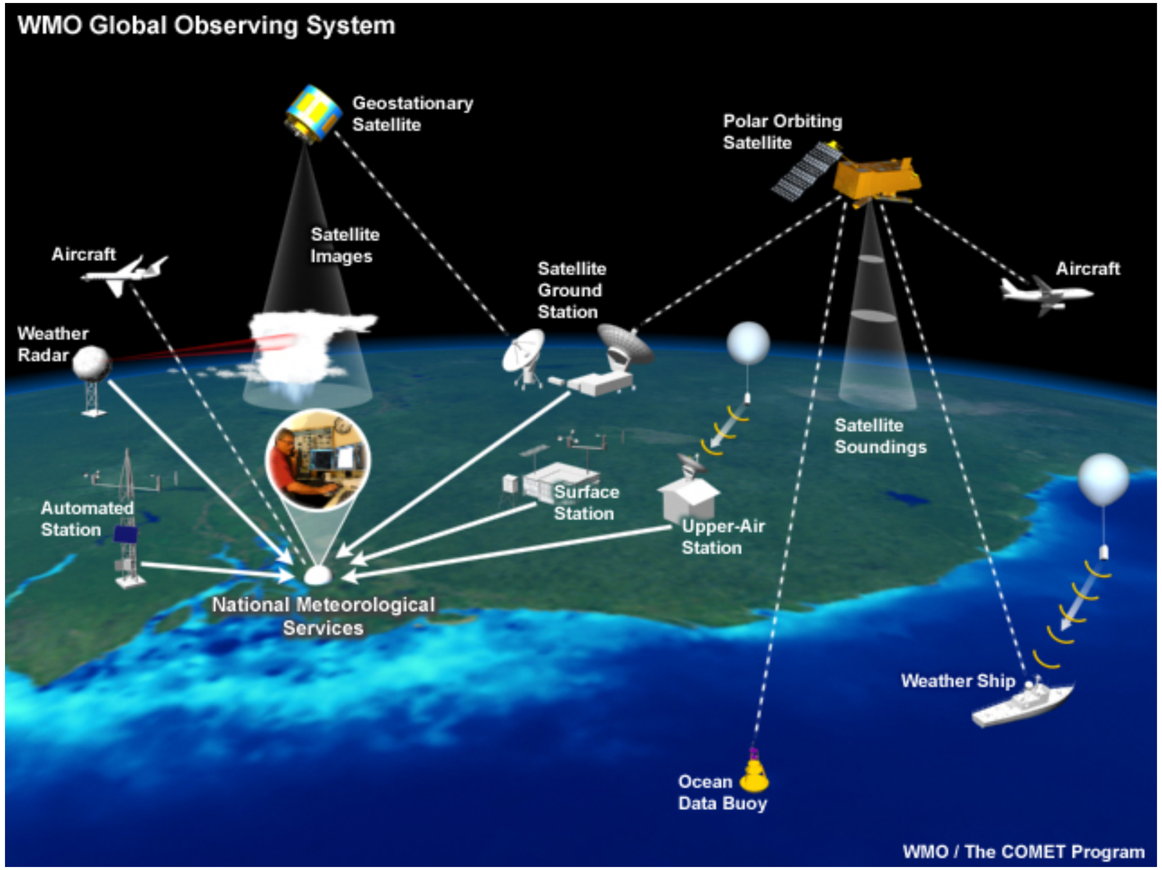
Health of the Atmospheric Observing System



Thanks to email contributions from Joan Alexander (CORA), Jennifer Hasse (SIO), George Huffman (NASA), Gail Jackson (NASA), Nick Nalli (NOAA), Brian Nelson (NOAA), Lazaros Oreopoulos (NASA), Marty Ralph (SIO), Duane Waliser (JPL).

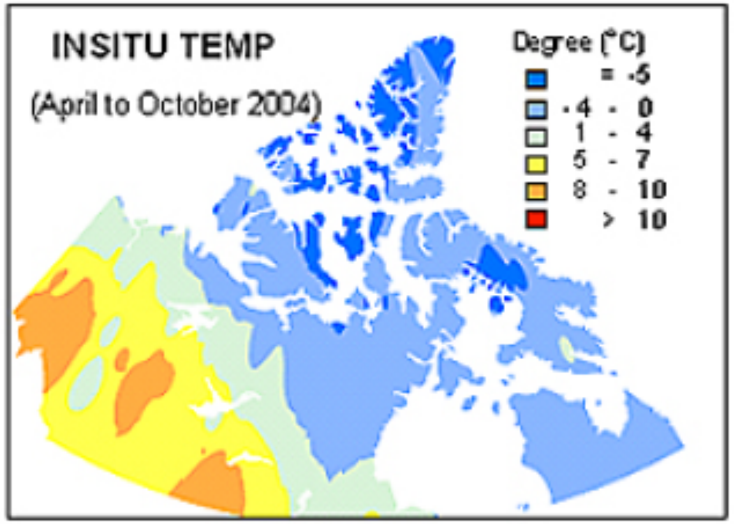
Framework for assessing the health of the atmospheric observing system

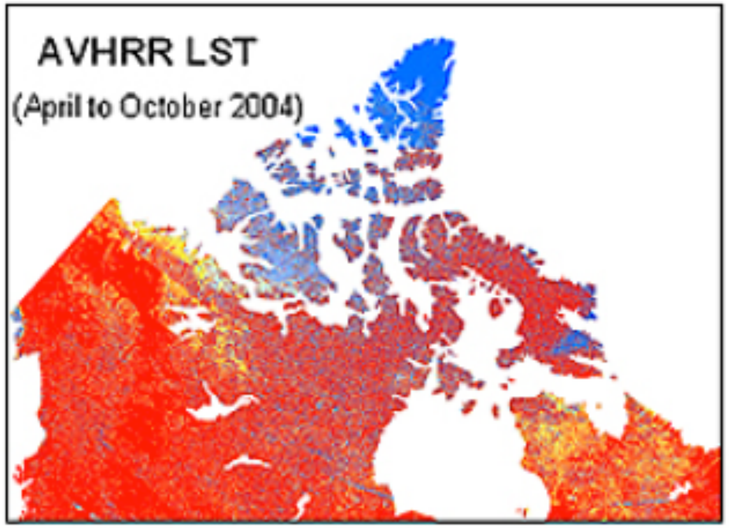
- Observations of essential climate variables (ECVs) in the atmosphere (GCOS Report 195, 2016, available online)
  - Surface meteorology (pressure, air temperature, humidity, winds)
  - Precipitation (rain, snow, etc.)
  - Surface radiation
  - Upper air (Air Temperature, Humidity, Winds)
  - Cloud Properties
  - TOA Radiation Budget
  - Aerosols
- Examples of key phenomena and our current ability to observe them
- Summary and recommendations/discussion points

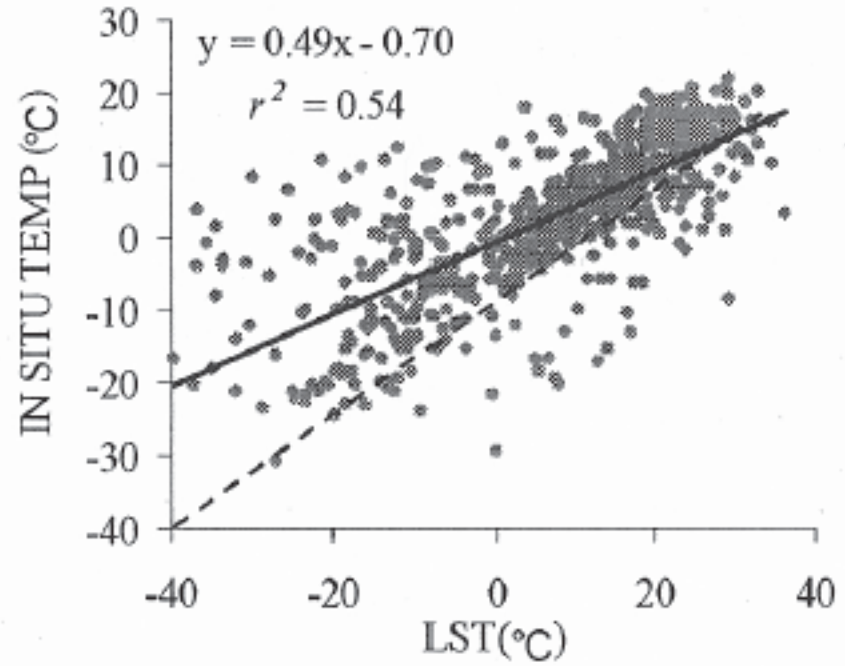
Surface Pressure, Air Temperature, Humidity and Winds

Contributing Networks	Status
GCOS Surface Network (subset of full WWW/GOS surface synoptic network) Full WWW/GOS surface synoptic network	**30% more stations in 2014 compared with 2002 and 80% more reports received.** Meteorological terminal aviation routine weather report (METAR) data have enhanced the networks. **More issues of quality for humidity than for temperature due to wide range of instruments.**
Moored buoys and ships	**Ship observations declined over ocean basins from 2002 to 2014 but increased around coasts.** Moored buoys have increased significantly. **Decline in the VOS has led to a significant lack of air temperature and humidity measurements over the ocean needed for estimating surface sensible and latent heat fluxes.** Availability of measurements from long-term, high-quality moorings is inadequate to evaluate the stability of SST from satellite measurements, except in the tropical Pacific.
Drifting buoys	Surface pressure sensors are only on a limited number of drifting buoys but are increasing.
Additional national networks	**More in situ air temperature measurements are needed in certain surface regimes** (high altitudes, desert, high latitudes, deep forest), in order to enable the optimum use of LST to help to estimate air temperature in these places.
Satellite air temperature	**Satellites do not directly measure surface air temperature.** Independent air surface measurements are needed for surface.
Visible, infrared and microwave (latter over ocean) all provide water vapor profile information but sensitivity to surface layer is small so measurement is indirect inferred from deeper layer values.	**Only indirect measurement and infrared coverage is clear sky only.** Microwave sounders contribute but with coarser spatial resolution. The health of the GOS with respect to microwave sounders quite good today and in the future. CMA committing to the early morning orbit is an important accomplishment by WMO and CGMS and microwave sounder coverage by EUMETSAT and NOAA will provide sustained observations until at least 2040.
Global Navigation Satellite System (GNSS) radio occultation (RO) measurements contribute to inferring the surface pressure but are not able to provide absolute anchor measurements at present.	**Continuity for GNSS RO constellation needs to be secured** as current COSMIC satellites beyond expected life and failing. COSMIC-2 is currently only guaranteed to cover tropical latitudes. **Commercialization of RO a concern.**

Satellite 2-m Air Temperature



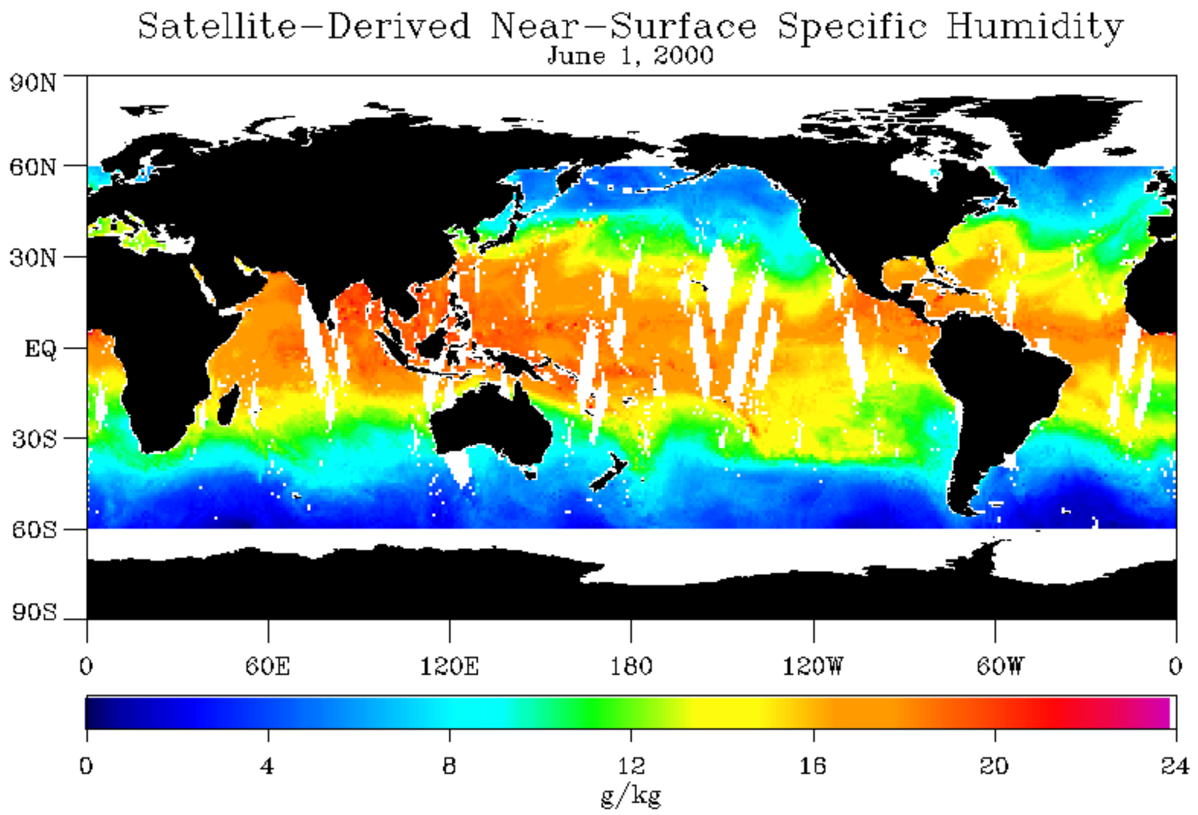




Li et al. (2013, *Prairie Perspectives*)

Air temperature relationship to LST breaks down for surface temperatures below freezing in this region of Canada. Use of in situ network increases 2-m air temperature retrievals.

Satellite 2-m Humidity



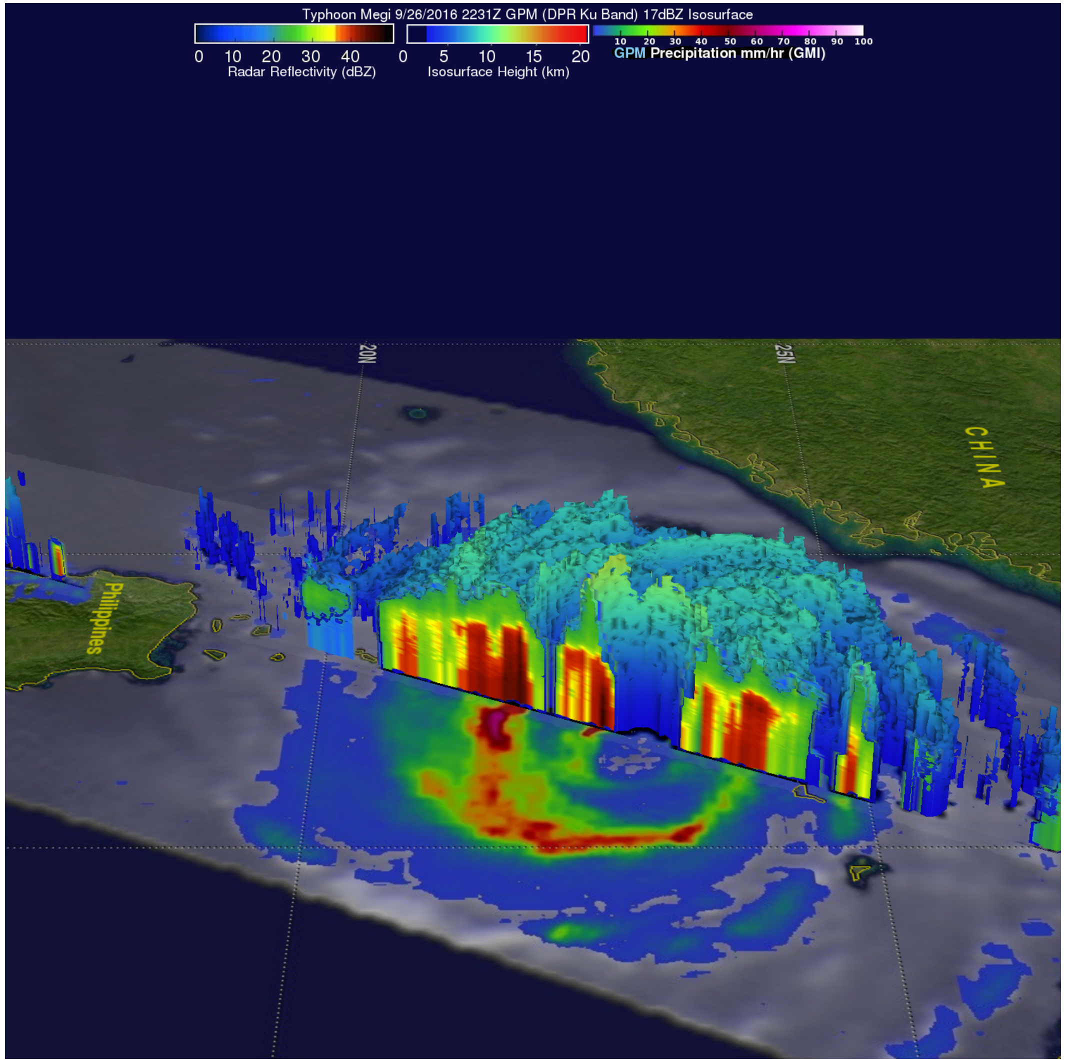
Jackson and Wick (2010, *J. Atmos. Oceanic Technol.*) use atmospheric sounder, SST and total column water vapor to derive 2-m humidity. Coverage only over oceans and in clear-sky conditions.

Precipitation

Contributing Networks	Status
GCOS Surface Network (subset of full WWW/GOS surface synoptic network) Full WWW/GOS surface synoptic network Additional national meteorological and hydrological gauge networks; island networks	**Quality of data and quantity of reports are variable** but data are analysed and archived. **Limited coverage in time and space**. Most countries operate national high-resolution precipitation networks, but **data are often not available internationally**, or available only with time delay.
Surface-based radar networks	Radar data not globally exchanged but some regions now have good networks. **Homogenization of radar precipitation is complex and blending radar and gauge precipitation is a long-term objective and still at a very early stage of development.**
Moored buoys	**Very limited observations** (e.g. TAO/TRITON buoys) available which were used to validate the Tropical Rainfall Measuring Mission (TRMM).
Passive microwave imagers on several polar satellites contribute. GSN/IR products from geostationary improve temporal coverage but are less accurate.	**Global Precipitation Measurement (GPM) satellite replacing TRMM has improved coverage at high latitudes. GPM (and CloudSat) are able to observe falling snow but error bars are high for both**, part of the problem is the instrumentation (surface clutter, not sensitive enough) but part of the problem is having accurate surface measurements of falling snow for validation. **Most microwave imagers are beyond their design lifetime and a future gap in the observing system of microwave imagers is likely.** It is important to have a "constellation" of these satellites to improve temporal sampling such as with TMPS, IMERG. Requires a cost commitment by the agencies.
Precipitation radar on research satellites (TRMM and GPM)	GPM can only observe precipitation down to 0.2 mm/hr (leaving much unmeasured at lower rates/ higher latitudes) – cost & engineering challenge. CloudSat can measure lower RR but does not scan to get a wide swath. Having a 3-frequency radar would allow for drop sizes of most of the non-precipitating cloud particles. **Uncertainty for continuity of precipitation radar, temporal and spatial sampling limitations.**

Table data adapted from Gail Jackson (NASA) and GCOS Steering Committee, 2016: The Global Observing System for Climate: Implementation Needs. WMO, GCOS-200 (GOOS-214), 342pp.

Typhoon Megi, Northwest Pacific, 26 September 2016



Precipitation Radar Reflectivity

GPM Precipitation

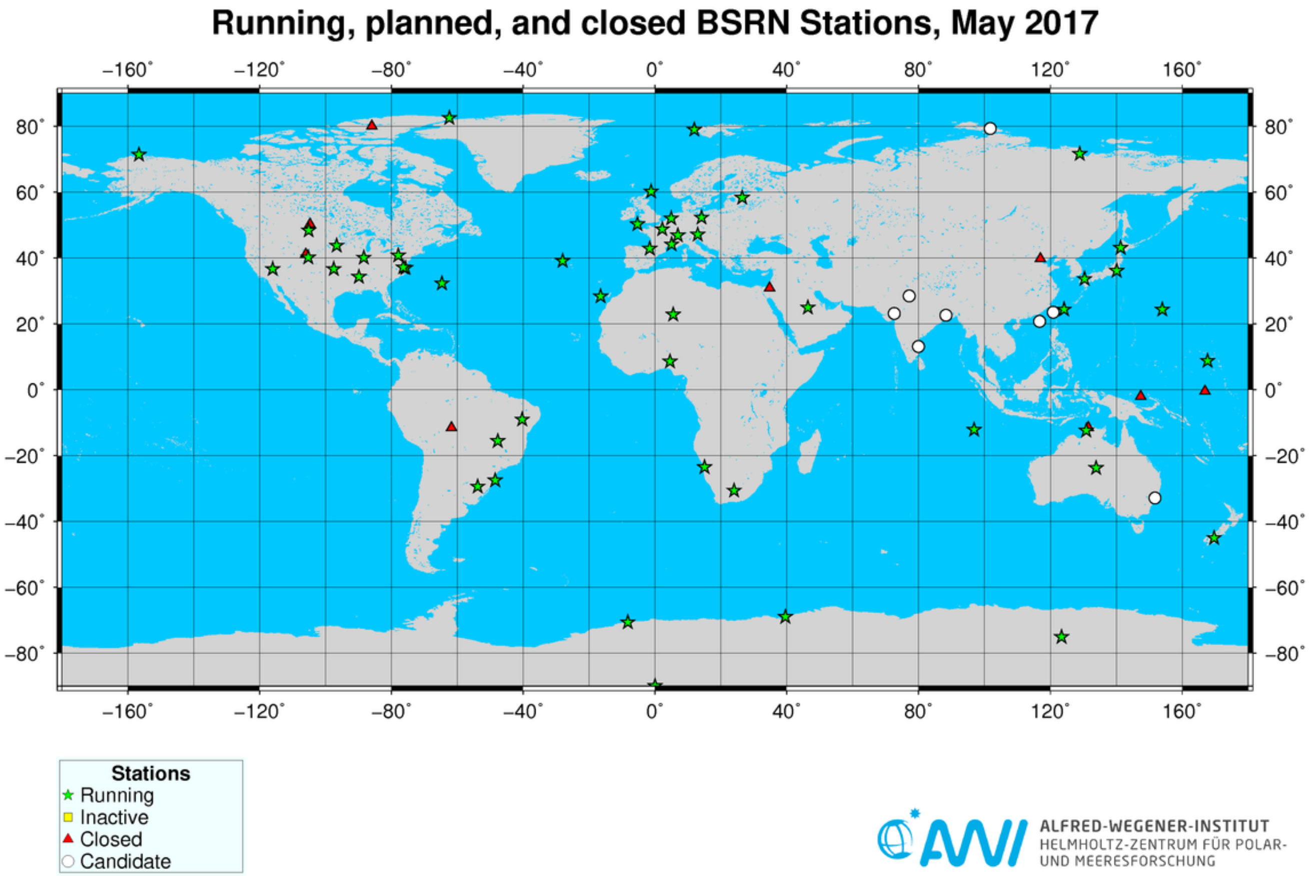
Surface Radiation

Contributing Networks	Status
GCOS BSRN (Baseline Surface Radiation Network)	Coverage limited (59) but 10 more stations added since 2009, though 2 Arctic stations closed. **Continuity needs to be secured. Expand geographically to be more representative.**
WWW/GOS surface synoptic network	**Quality and coverage of routine radiation data (mainly incoming solar in monthly CLIMAT reports) is variable.**
Additional national networks	**Limited availability of high-quality data in national networks**
Moored buoys	Solar fluxes and longwave radiation available over the ocean from some moored buoys and research vessels.
Geostationary and polar orbiter visible and infrared data	Incident solar radiation inferred from satellite visible radiances. For infrared, satellite data are used to estimate cloud and near-surface parameters and thermodynamics fields are typically taken from reanalyses. **Not a direct measure of incoming surface radiation. Need for high quality aerosol optical depth estimates over land at high spatial and temporal scales to enhance the accuracy of the surface net SW flux derived from satellite.**

Table data adapted from GCOS Steering Committee, 2016: The Global Observing System for Climate: Implementation Needs. WMO, GCOS-200 (GOOS-214), 342pp.

Baseline Surface Radiation Network

59 stations



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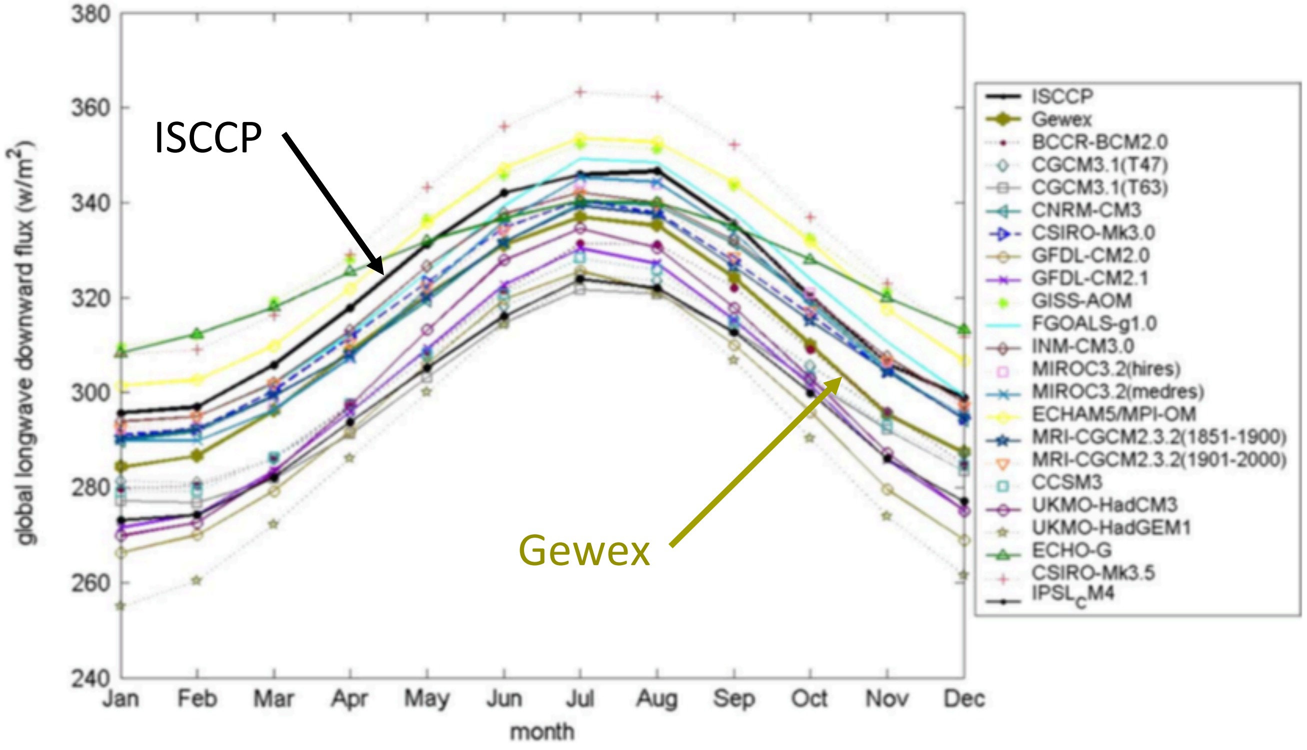
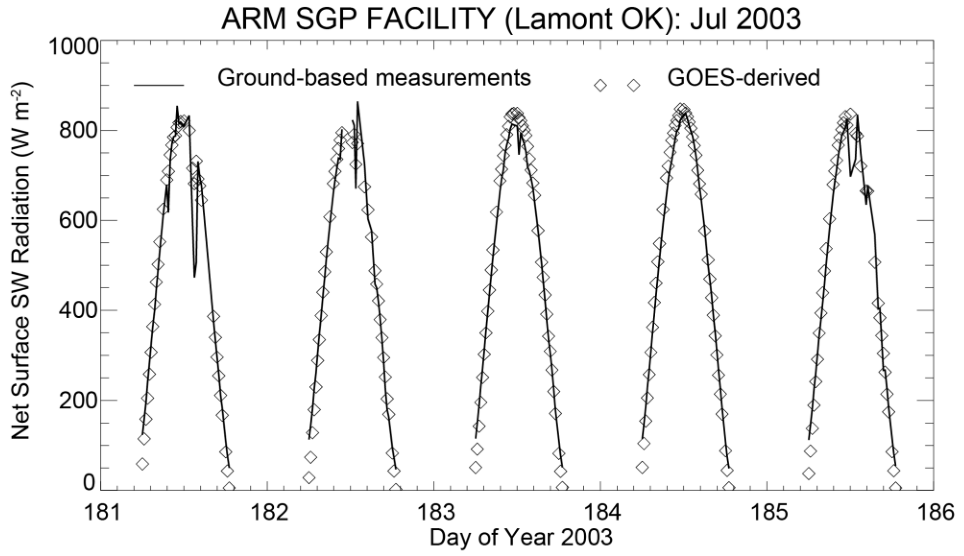
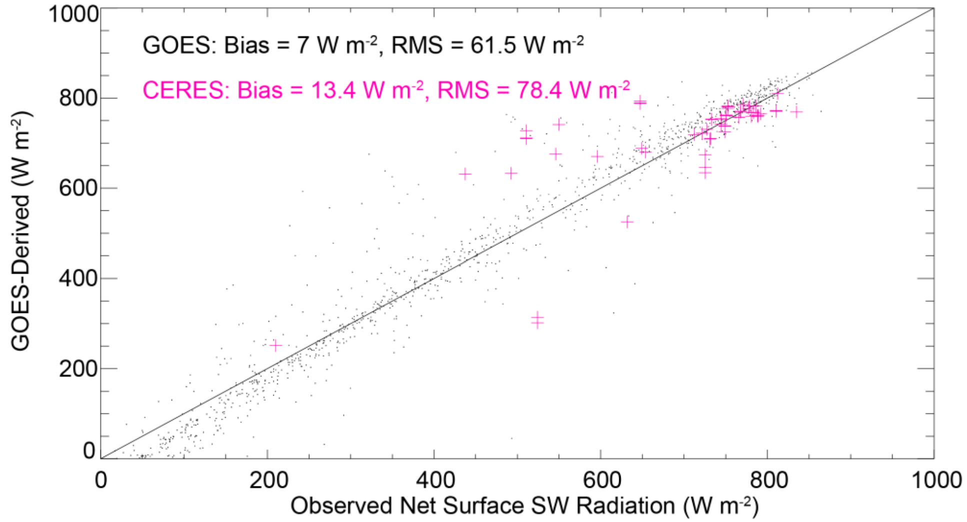
Surface Radiation From Satellites and GCMs



Liang et al. (2010, *IEEE*)





Inamdar and Guillevic (2015, *Remote Sen.*)

Upper-Air Temperature, Humidity and Winds

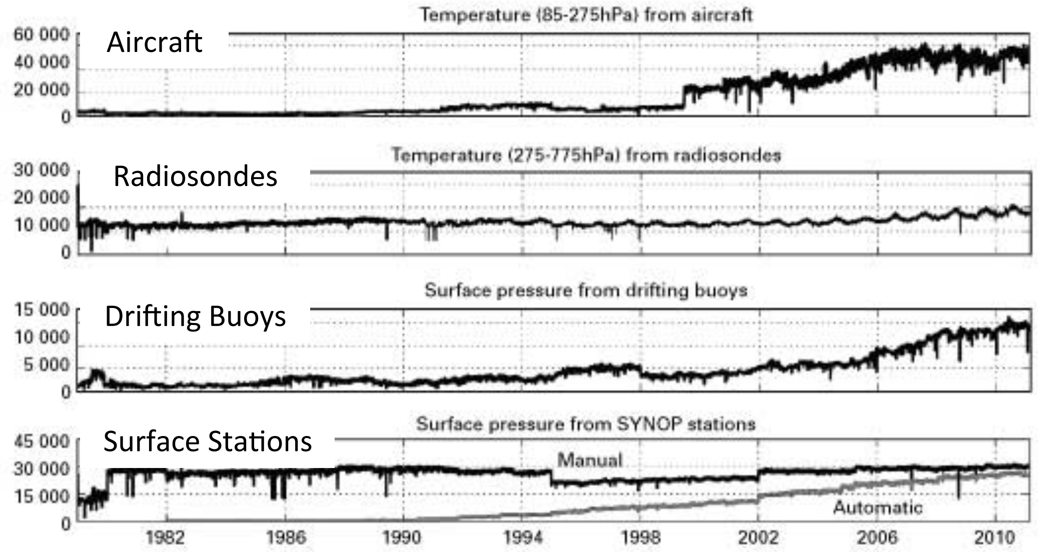
Contributing Networks	Status
Reference network of high-quality and high-altitude radiosondes (GRUAN). GRUAN will provide long-term, continuous, high-quality in situ atmospheric profile observations for climate monitoring, calibration of satellite observations and products, and climate process studies (Bodeker et al. 2016, *BAMS*).	GRUAN is now well established with 22 stations participating and 7 already certified. **Biased to land over ocean regions, Northern Hemisphere mid-latitudes over Southern Hemisphere and Tropics.**
GCOS Upper-Air Network (subset of full WWW/GOS radiosondes network)	**A 10% increase in number of 500 hPa reports and 20% increase at 30 hPa from 2002 to 2014. Improvements in data quality seen. Accuracy of water-vapor measurements is improving but is still inadequate for climate purposes in the upper troposphere and lower stratosphere.**
Full WWW/GOS radiosonde network	The move to BUFR has started but more remains to be done for all countries to be reporting. Many stations do not provide two observations each day.
Commercial aircraft	The Aircraft Meteorological Data Relay (AMDAR) program provides routine flight level and profile wind and temperature measurements. Needs expansion to include all major airlines and major airports. **Observations limited to specific levels except near airports.**
Wind profilers	Profiler sites mainly over Europe, Japan and USA but **USA sites are being phased out.**
PILOT balloons (drifting balloons for winds)	Typically 350 sites globally distributed
Atmospheric motion vectors from geostationary and polar orbiters	**Geostationary atmospheric motion vector (AMV) accuracy and spatial and temporal density improving.** The poles are covered with AVHRR, VIIRS, MODIS, Multi-angle Imaging SpectroRadiometer (MISR) and Atmospheric InfraRed Sounder (AIRS) AMVs. The low Earth orbit (LEO)-GEO AMVs and Eumetsat's global Metop AVHRR have filled the long-standing gap in coverage (40°-70° N/S). New imagers, such as Himawari-8 AHI of the Japan Meteorological Agency (JMA), with better horizontal resolution, **improved temporal coverage and more spectral channels are becoming available in geostationary orbit**. Imagers operated by China, Republic of Korea, USA and Eumetsat will eventually have similar capabilities.

Upper-Air Cont…

Contributing Networks	Status
Doppler wind lidar from satellite (low-level winds)	Awaiting Atmospheric Dynamic Mission (ADM)/Aeolus demonstration; **no continuity planned after this**
GNSS RO (Radio Occultation)	**Continuity for GNSS RO constellation needs to be secured** as current COSMIC satellites beyond expected life. COSMIC-2 is currently only guaranteed to cover tropical latitudes but several other missions provide RO data. **Polar constellation needs to be secured. High-latitude data are necessary for climate-quality analysis. Information on water vapor at high vertical resolution. Coarse horizontal resolution. Commercialization of RO an issue.**
Microwave and infrared imagers and sounders	**Ensured continuity of Infrared Atmospheric Sounding Interferometer (IASI) and Cross-track Infrared Sounder (CrIS) and Advanced Microwave Sounding Unit (AMSU)-like radiances for 3 orthogonal polar orbits. Highly vertically resolved water-vapor observations, especially in the lower troposphere, are crucially needed which are beyond the capabilities of these sensors. Sounders cannot get to the surface, trouble near coastlines and over topography.** MW imagers (SSM/I, TMI, GMI) provide total column amounts, limited frequency, best over ocean. Geostationary infrared images (GOES) provide high temporal resolution water-vapor data, clear-sky only.
Infrared and MW limb sounders and solar occultation	**No continuity of current limb sounders for stratospheric water vapor**

Table data adapted from GCOS Steering Committee, 2016: The Global Observing System for Climate: Implementation Needs. WMO, GCOS-200 (GOOS-214), 342pp.

Global Observing System Atmospheric Data Availability

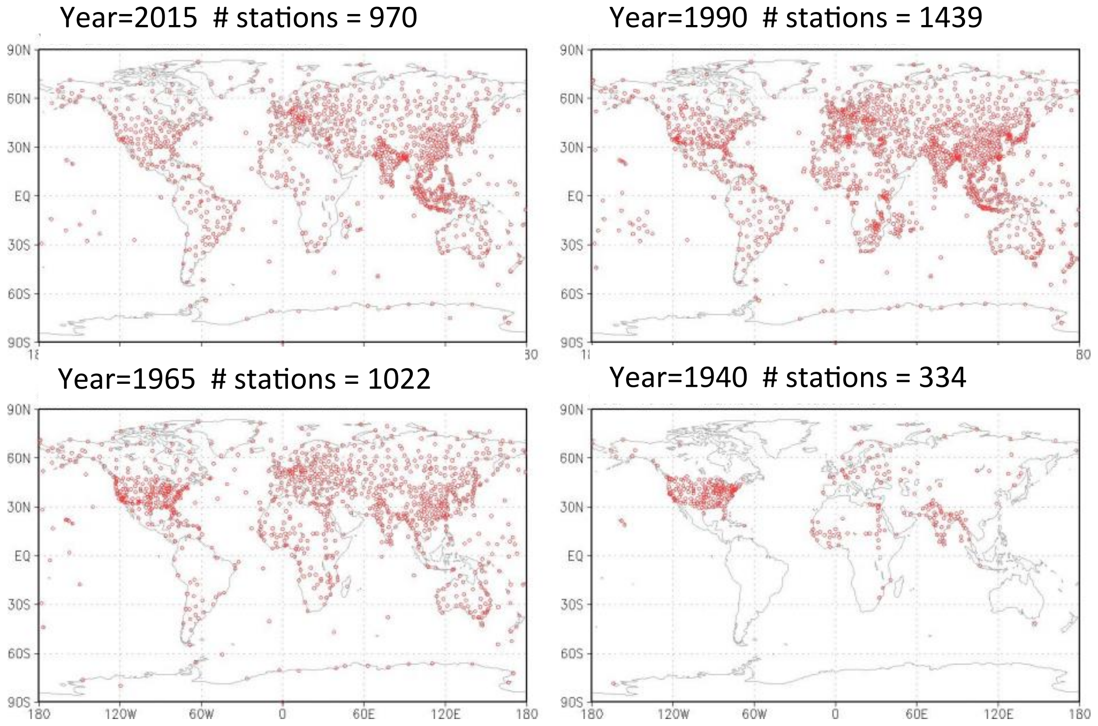


- Aircraft and global drifter observations show largest increase over past 30 years
- Radiosonde and surface station data mostly stable or increasing over this time

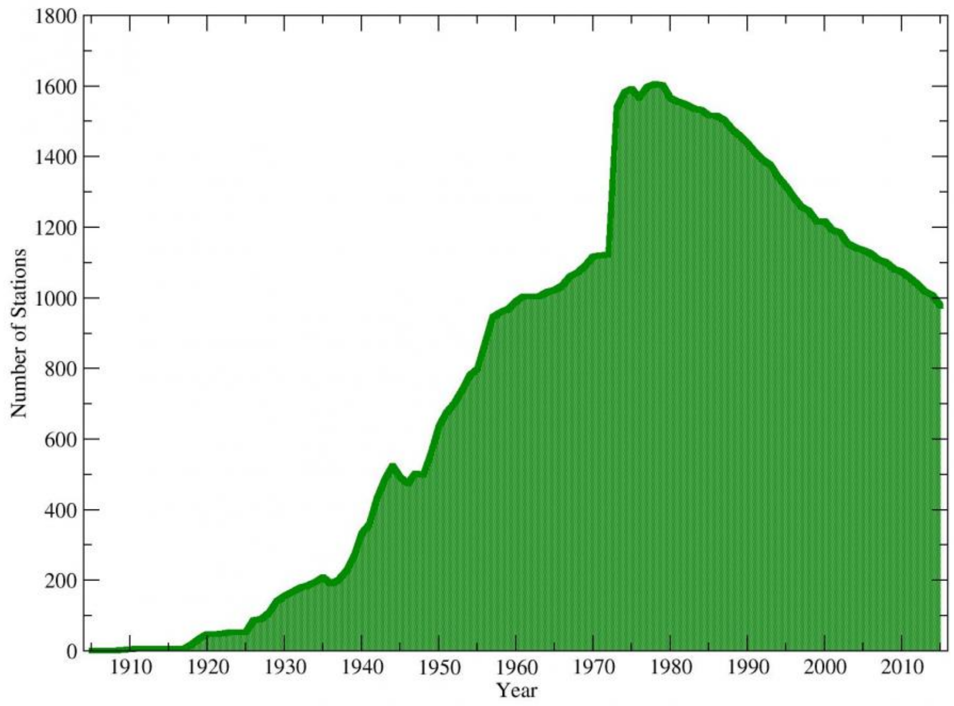
Image source: Simmons, A., 2011: From Observations to Service Delivery: Challenges and Opportunities. *WMO Bulletin*, **60** (2), 96-107.

Integrated Global Radiosonde Archive

Geographic distribution of stations

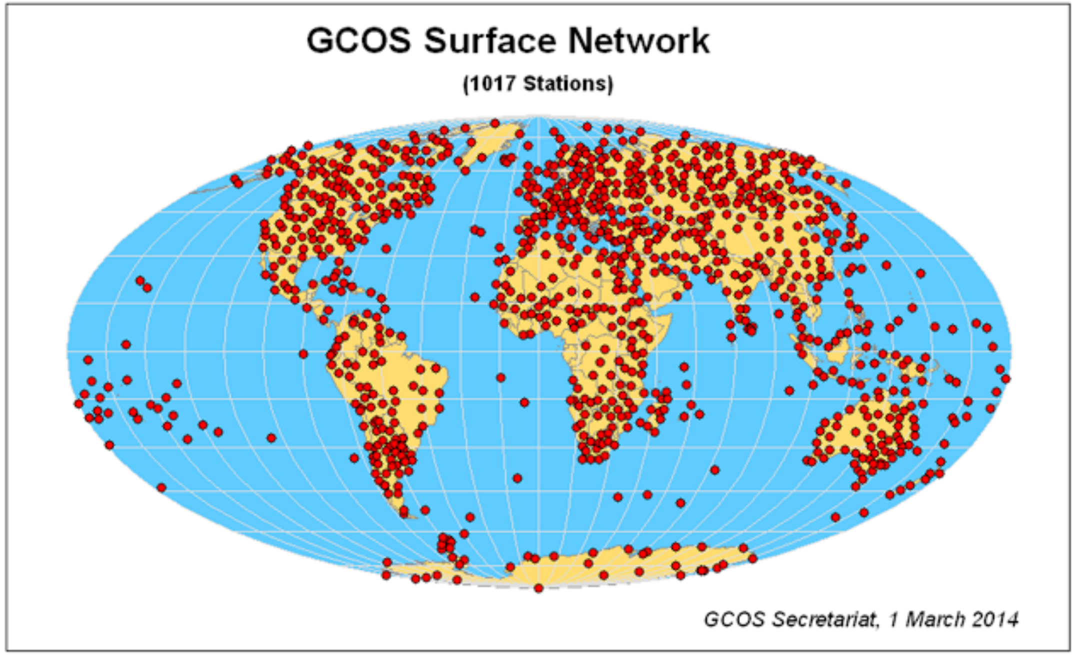


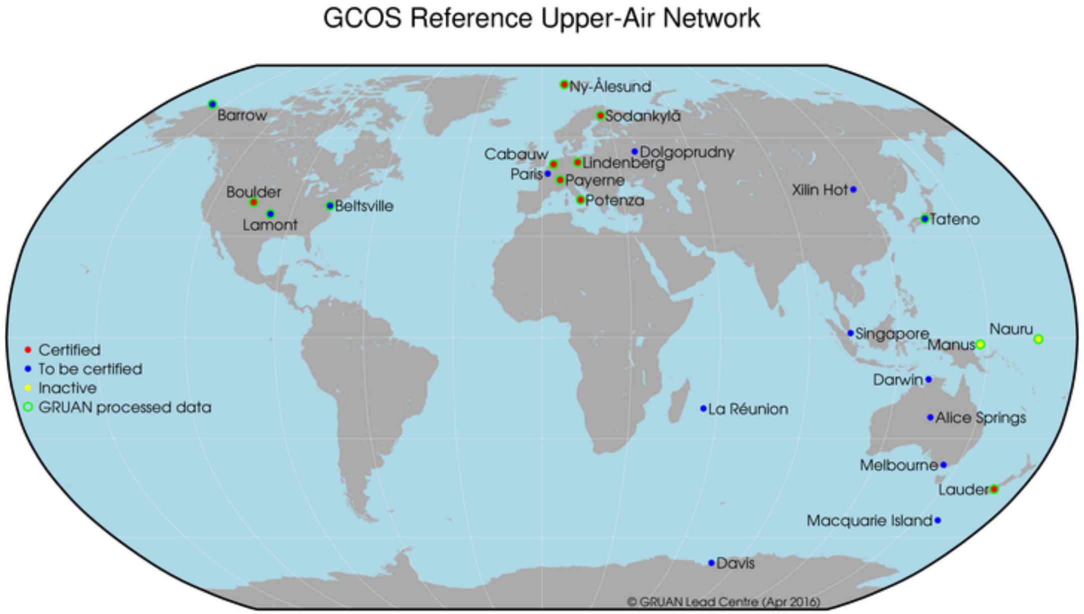
Number of stations reporting data



Images accessed from https://www.ncdc.noaa.gov/data-access/weather-balloon/integrated-global-radiosonde-archive.

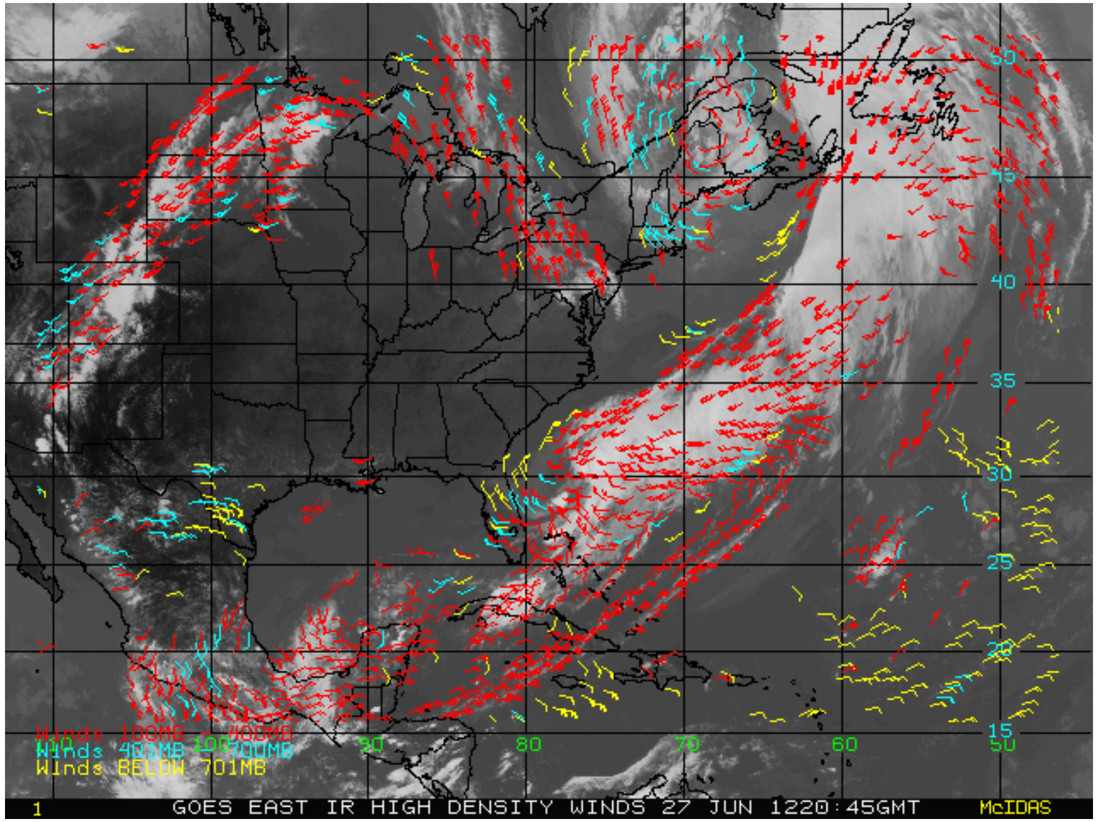
GCOS Surface and Reference Upper-Air Networks

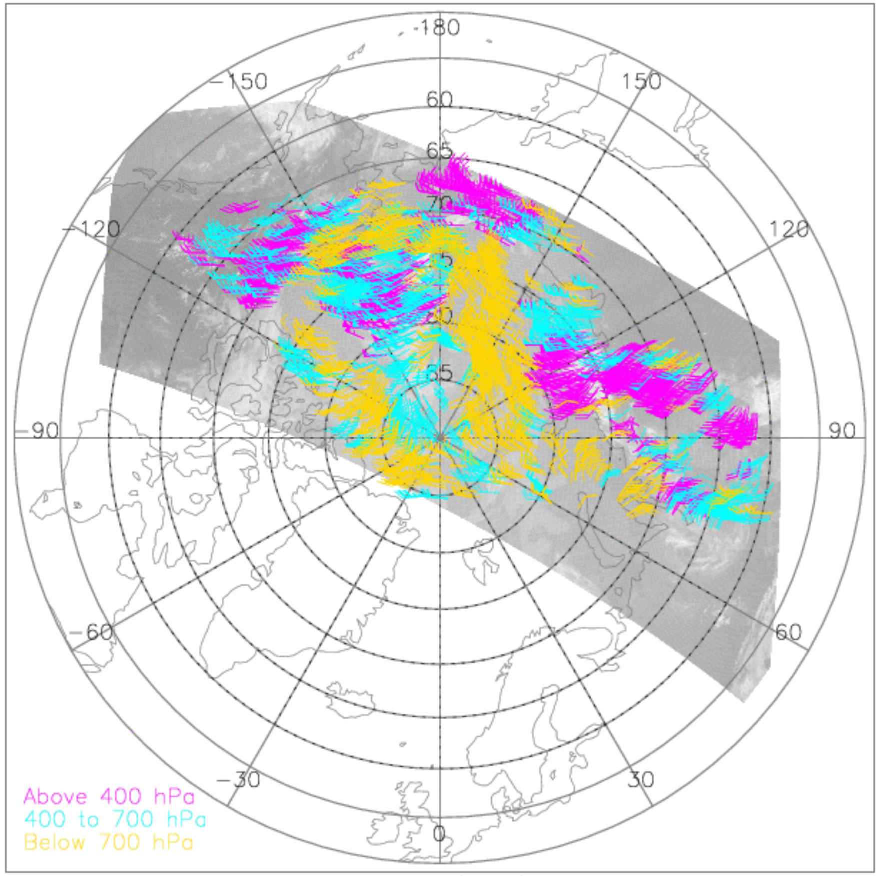




(GRUAN, Immler and colleagues, 2010)

Cloud Vector Winds





VIIRS POLAR WIND on 08/08/2017 21:12 UTC

Cloud Properties

Contributing Networks	Status
Surface observations (GSN, WWW/GOS, VOS)	**Surface observations of cloud cover provide a historical but uncertain record and continuity is a concern; reprocessing of cloud data is needed.**
Surface cloud radar and lidar	Research-based networks only
VIS, IR and MW radiances from geostationary and polar orbiting satellites	**Cloud-top temperature, microphysical properties and coverage are all operational and have good continuity.** Passive imagers like MODIS/VIIRS have limitations on the kind and quality of information they can provide. **Many cloud observing capable instruments or satellites are reaching end-of-life/mission and it is unknown when (or even whether) we will fly successor instruments. Commitment by US for cloud measurements beyond operational imagers is not a given.** Technology exists, algorithms are capable and continue to mature, but cost is a major impediment. **Fortunately, imagers on GEO satellites are becoming more capable (AHI on Japanese Himawari-8; ABI on GOES-16; eventually FCI on MTG). There are coverage gaps, but temporal evolution of the atmosphere and clouds can be monitored much better than from sun-synchronous orbits.** **Some cloud properties still challenging to obtain**, e.g., particle concentrations, ice crystal shapes/habits. Most difficult detection is low cloud over bright surface or in the presence of a large temperature inversion, but active (radar and lidar) measurements are quite capable in these situations; retrieving cloud properties other than extent can still be a challenge for certain cases.
Cloud radar and lidar on research satellites	**No continuity assured of these research satellites.**

Table data adapted from Lazaros Oreopoulos (NASA) and GCOS Steering Committee, 2016: The Global Observing System for Climate: Implementation Needs. WMO, GCOS-200 (GOOS-214), 342pp.

Top of the Atmosphere Earth Radiation Budget

Contributing Networks	Status
Broadband short- and longwave and total and spectral solar irradiance	Current RB measurements will continue with JPSS-1 (to be launched 4Q of FY2017). **The next generation RB-measuring instrument RBI is slated for JPSS-2, but its elimination has been proposed in the President's budget.** **Our current radiation budget (RB) measurement capabilities using CERES do not allow us to measure the Earth Radiation Imbalance (difference between absorbed solar and thermal IR radiation emitted to space) nowhere near close to accuracies needed for understanding the impacts of the drivers of climate change. Non-US RB instruments do not have coverage, or accuracy, or appropriate products to match CERES for climate applications (e.g., GCM evaluation).**

Table data contributions from Lazaros Oreopoulos (NASA).

Aerosols

Contributing Networks	Status
WMO Global Atmospheric Watch World Data Center for Aerosols (lidar, radiometers, land-based, airborne, ship-based, mobile and stationary platforms)	Volunteer network of aerosol observations from around the world. **Uncertain of data quality or coverage issues.**
Satellite based lidar, AVHRR (ocean only), MODIS and MIRS (land and ocean)	We can detect column amounts (aerosol optical depth) over dark surface quite well (away from clouds); also making progress over bright surfaces (incl. clouds) with recent algorithms, depending on aerosol type (absorbing aerosols better detected in these situations). **Vertical distribution of aerosol is important to know, but more challenging to obtain.** Need to know near-surface amount for air-quality applications. Lidars very helpful for this. **Detecting aerosol type and chemical composition from space still a challenge.** Polarimetry and multi-angle capability will help. **Still ways to go for extracting aerosol information relevant to cloud processes (aerosol number concentration below cloud base, aerosol fraction that acts as CCN). US commitment for aerosol detection and monitoring for climate applications not as strong as it should be.** Eumetsat EPS-SG will fly the 3MI multi-angle polarimeter operationally and will improve aerosol retrievals. As with clouds, better GEO imagers will improve the outlook for continuous aerosol monitoring.

Table data contributions from Lazaros Oreopoulos (NASA).

Upper Troposphere/Lower Stratosphere (UTLS) Processes

Requirement 1: Observe water vapor, temperature, ice clouds, and ozone at high vertical resolution in the tropics. Quantify fine-scale troposphere-stratosphere exchange of ozone at midlatitudes, with ozone important as a radiatively active species, as well as important player in air quality.

Requirement 2: High spatio-temporal measurements of temperatures/winds/ice to quantify tropical wave influences on cirrus.

- The former could come from high-resolution limb sounding satellites, and SPARC (Stratosphere-troposphere Processes And their Role in Climate) has been advocating for such measurements.
- The latter will be measured by instruments that will fly on long-duration isopycnal balloons in the Strateole-2 campaign.

Note that reanalyses have large persistent forecast errors in the tropical UTLS due to very sparse wind measurements and lack of balance between winds and temperatures.

Atmospheric Rivers

Obs. Requirements: Precipitation, evaporation and convergence of column moisture measurements, boundary layer winds are key for the convergence.

- Water vapor is measured by RO, IR sounders and total column water vapor is measured by microwave and IR imagers.
- Winds in the troposphere are not observed with sufficient time and space scales and are not easily derived in the ABL.
- Satellite lidar being tested by ESA for ABL winds, poor sampling.
- Evaporation indirectly measured from satellite, needs further development.
- Precipitation has problems near topography (particularly snow) and near the coastlines.

Summary of Obs Needs

- Surface and upper-air stations have climate regime and hemispheric biases that need consideration.
- No global surface aerosol network.
- Lack of surface and upper-air observations over global oceans.

- Satellite platforms lack continuity for: limb sounders, RO at high latitudes, radar, microwave imagers, scatterometers, space-borne lidar.
- Satellite derived vertical distribution of water vapor, aerosols, cloud properties a challenge.
- Satellite vertical temperature and moisture profiles do not penetrate the ABL.

Recommendations / Discussion Points

- Need more observations of the atmosphere over open ocean regions, in different climate regimes and at upper troposphere lower stratosphere interface.
- Error characterization of in situ data seems to be improving, data densification will help. Satellite data error characterization limited by lack of observations.
- Need data sharing plans for in situ observing networks to increase the number of observations going into international data bases. May be transferable to guiding privatization of data in US (e.g, US RO & surface GPS network).
- Encourage continuity in satellite platforms, maybe through the Coordination Group for Meteorological Satellites (CGMS).
- Challenge 1: Obtain global estimates of evaporation (ocean/land). Important for global water cycle/global energy cycle.
- Challenge 2: Obtain open ocean estimates of low-level winds for water vapor transport estimation/forecast & reanalysis model constraint.
- Findings from this POS discussion should be shared with NSA decadal survey for space measurements (end of year release, contact Duane Waliser).

Stratéole-2 Overview

Project Principal Investigators (US):
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Lars Kalnajs & Terry Deshler (LASP), Sean Davis (NOAA CIRES)
Project PIs (France):
Albert Hertzog & Riwal Plougonven (LMD),
Philippe Cocquerez & Stephanie Venel (CNES)

Summary of Scientific Objectives

- Stratéole 2 will use long-duration balloon campaigns to explore dynamical and physical processes that control the transfer of trace gases and momentum between the equatorial Upper Troposphere and Lower Stratosphere (UTLS).
- The observations provide information needed to improve the parameterization of waves in climate models and to understand their interactions with deep convection in the deep tropics, as well as cirrus formation and dehydration that controls radiative effects in the stratosphere.

3 campaigns during boreal winter (DJF) to address convective processes and the most intense dehydration across the tropical tropopause layer

- *Validation campaign late 2018 (5 flights, one of each instrument configuration)*
- *1st science campaign late 2020 (20 flights)*
- *2nd science campaign late 2023 (20 flights)*

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Upper troposphere / Lower stratosphere wave observations

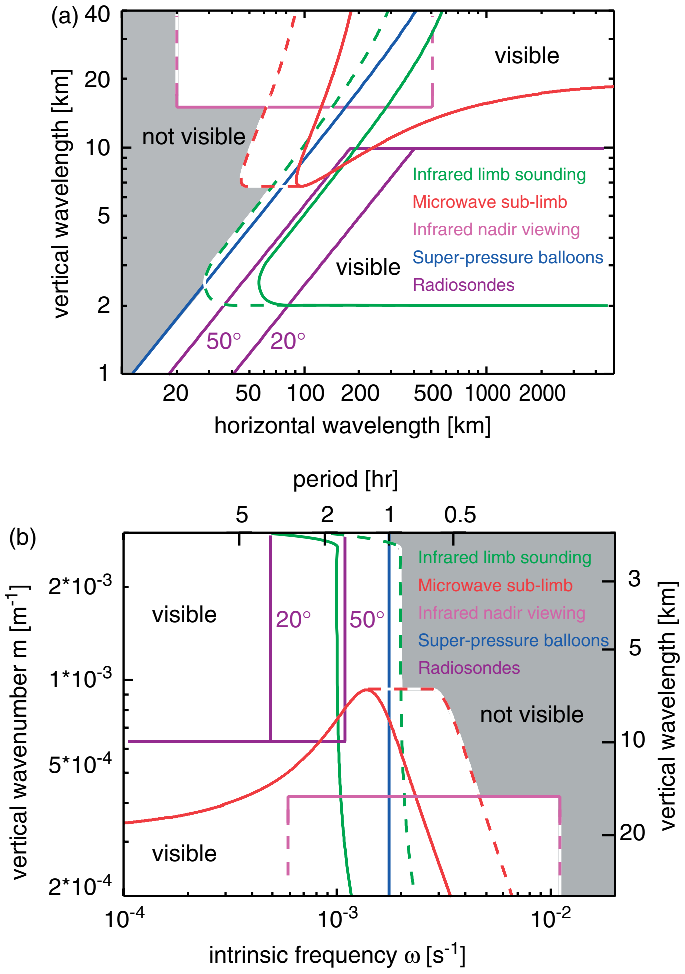


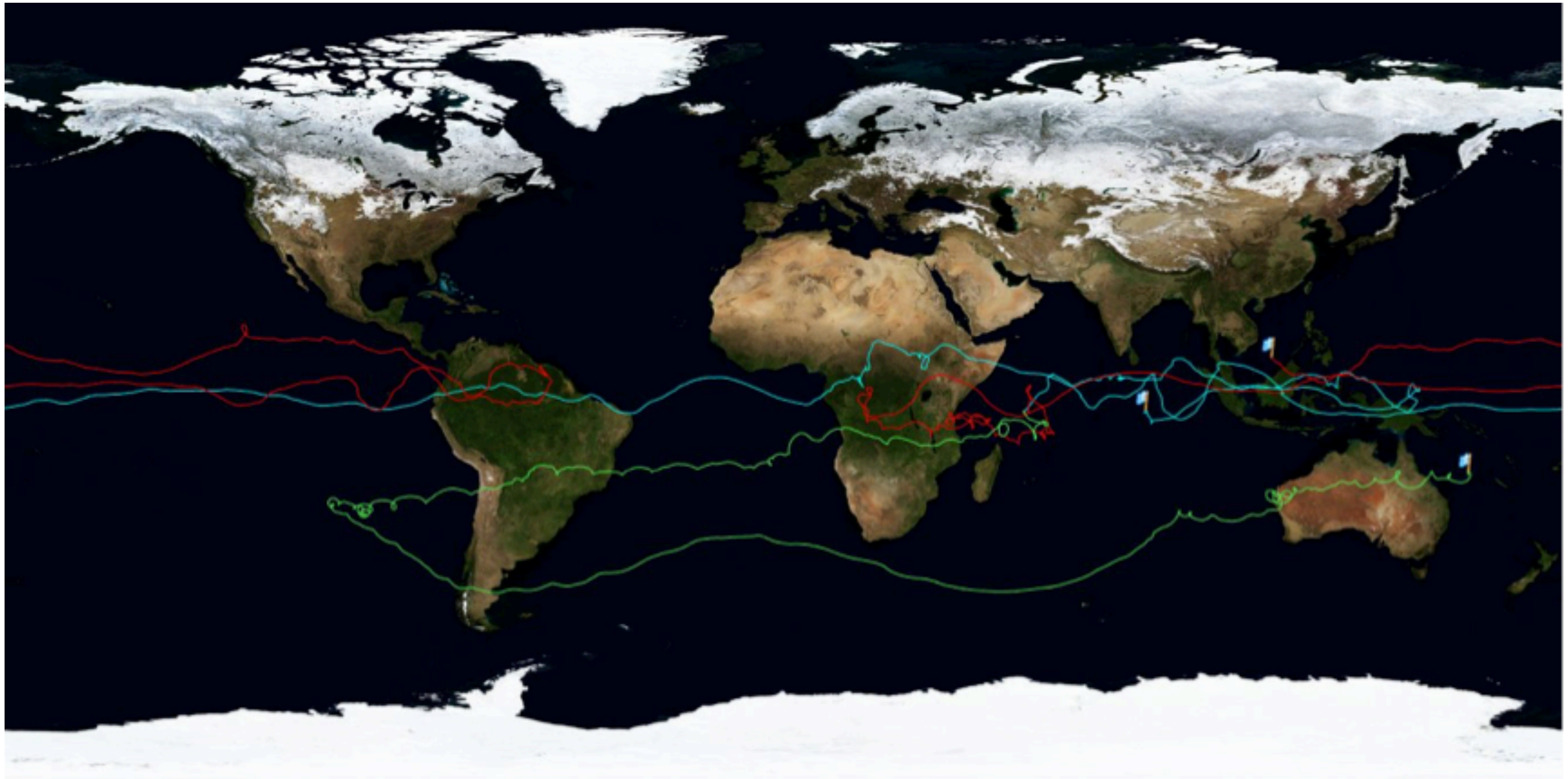
Figure 8. Typical visibility limits as functions of horizontal and vertical wavenumber (top) and frequency/vertical wavenumber (bottom) for various satellite and balloon measurement techniques. Shaded regions are not visible to any of the techniques. After Preusse *et al.* (2008).

Alexander et al., 2010, QJRMS.

- The balloons provide unique measurements of equatorial waves over the full spectrum from high frequency buoyancy waves to planetary-scale equatorial waves.

- New instrumentation extends the scales of observations further.

Test flights of super-pressure balloon system



- Early tropical test flights of the super-pressure balloon system during February - May 2010. The flight duration of the balloons was approximately 80 days near 20 km altitude. Some wave structure is visible in the traces of the balloon paths, and the reversal of the balloon paths when the QBO changed phase is also visible.

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