Physics 2506, Fall 2015

Atmospheric Data Assimilation and Retrieval Theory

Data assimilation involves combining observations with model output to obtain a consistent, evolving 3-dimensional picture of the atmosphere. This process is used to generate an initial state for producing forecasts at operational weather forecast centers. Data assimilation can also provide added value to observations by filling in data gaps and inferring information about unobserved variables. In this course, common methods of data assimilation (optimal interpolation, Kalman filtering, variational methods) are introduced and derived in the context of estimation theory. The use of these methods for satellite data retrievals will also be presented. A hands-on approach will be taken so that methods introduced in the lectures will be implemented in computer assignments using toy models.

Time: First week, Wednesday and Friday 10:00-11:00 am

Place: McLennan Laboratory MP505

URL: http://www.atmosp.physics.utoronto.ca/~dbj/PHY2506/

Instructor: Prof. Dylan Jones

Office: McLennan Laboratory 707B

Phone: (416) 978-4992

E-mail: dbj@atmosp.physics.utoronto.ca

Texts:

- Rodgers, C., 2000: Inverse Methods for Atmospheric Sounding, World Scientific Publishing.
- Lecture notes from Saroja Polavarapu will be distributed during class.

Assessments: Problems sets 50%, final project 50%.

Topics:

- Retrieval theory and inverse modelling
- Introduction to estimation theory
- Optimal interpolation
- 3D-variational methods
- The linear Kalman filter
- 4D-variational methods

References:

- Daley, R., 1991: Atmospheric Data Analysis. Cambridge University Press.
- Todling, R., 1999: Estimation Theory and Foundations of Atmospheric Data Assimilation, DAO Office Note 1999-01.
- Enting, I., 2002: Inverse Problems in Atmospheric Constituent Transport, Cambridge University Press.
- Swinbank, R., V. Shutyaev, and W. A. Lahoz, 2003: Data Assimilation for the Earth System, Kluwer Academic Publishers.
- Kalnay, E., 2003: Atmospheric Modeling, Data Assimilation and Predictability, Cambridge University Press.

What is data assimilation (DA)?

A framework for combining observations with model to produce an analysis that closely fits the observations.

Motivation (atmospheric context):

1) Observations provides limited spatial and temporal coverage - DA as interpolation
2) Produce more reliable forecasts of the state of the atmosphere using models – models can drift from reality, so we use DA to initialize forecasts
3) Combine data from difference sources, with different uncertainties, to obtain a consistent and optimal combined dataset

Examples of more general applications

1. **Navigation**
   One of the earliest applications that embraced the Kalman filter (newly developed in 1962) was that of designing navigation systems. It is still an important application of the Kalman filter. In a typical, self-contained navigation system, observations are collected and used to produce velocity corrections. The navigation system may be on board a rocket to Mars, a satellite in orbit, a missile over the arctic, a ship at sea or a car.

2. **Remote sensing**
   Indirect measurement of atmospheric parameters from space. Observations of radiation from the atmosphere are nonlinearly related to the retrieved quantity. Also, Moreover, there is no unique solution (many possible temperature profiles could result in the same measurement. Therefore, using some background information, such as a model forecast, the observations are combined with the background to produce a retrieval.

3. **Geophysics**
   The use of seismic activity, for example, to retrieve the structure or velocities within the Earth. The data is then arrival times and the retrieved quantities are densities or velocities.

4. **Tracer source inversion**
   We can use observations of atmospheric constituents (such as pollutants) to trace the original source of the chemical tracer and quantify the source amount. An obvious example is a nuclear accident that has not been reported. If the chemicals are inert, acting effectively like passive tracers, then Kalman smoothers or Four-Dimensional variational methods can be used to trace the original source.

5. **Weather forecasting**
   Data assimilation has been used to obtain an initial state for integrating a numerical weather prediction model since the 1970's. Early methods included statistical (or optimal) interpolation and analysis corrections. In the 1990's, variational methods became increasingly preferred. With the time evolution of forecast error statistics, these methods become sub-optimal Kalman filters. The literature in data assimilation for NWP (Numerical Weather Prediction) is very extensive. A good introduction is found in Daley (1991).

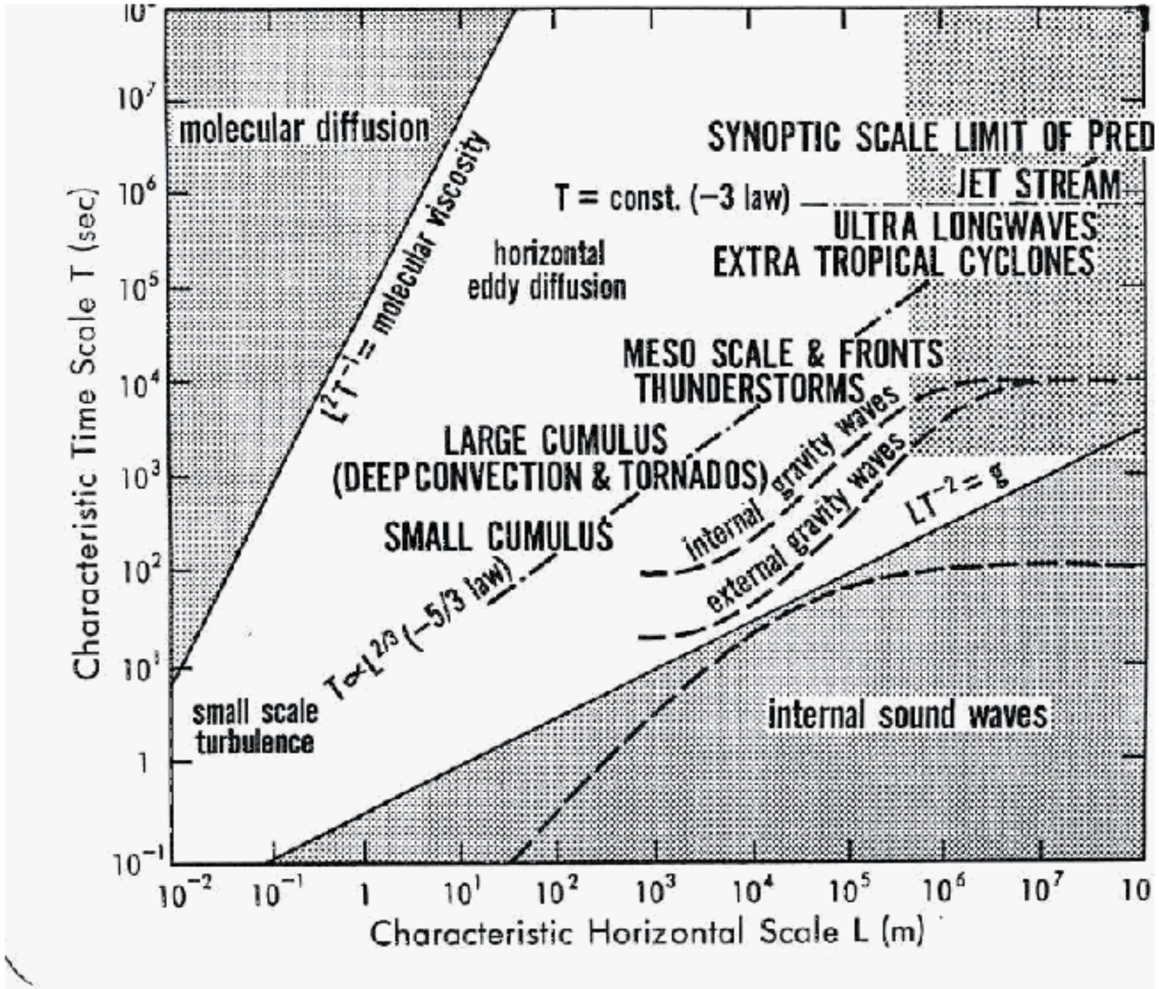


Figure 4. Characteristic horizontal and time-scales of atmospheric motions. After Smagorinsky (1974).

[From ECMWF lecture notes]

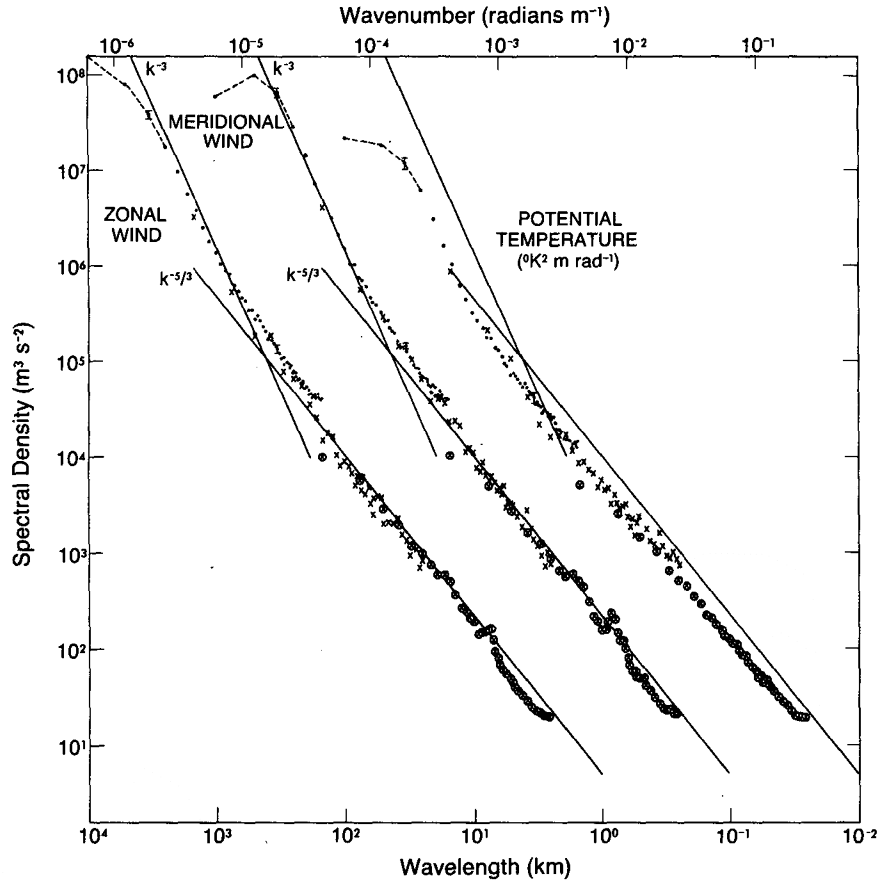


FIG. 3. Variance power spectra of wind and potential temperature near the tropopause from GASP aircraft data. The spectra for meridional wind and temperature are shifted one and two decades to the right, respectively; lines with slopes −3 and −5/3 are entered at the same relative coordinates for each variable for comparison.

[From Nastrom and Gage, 1985]

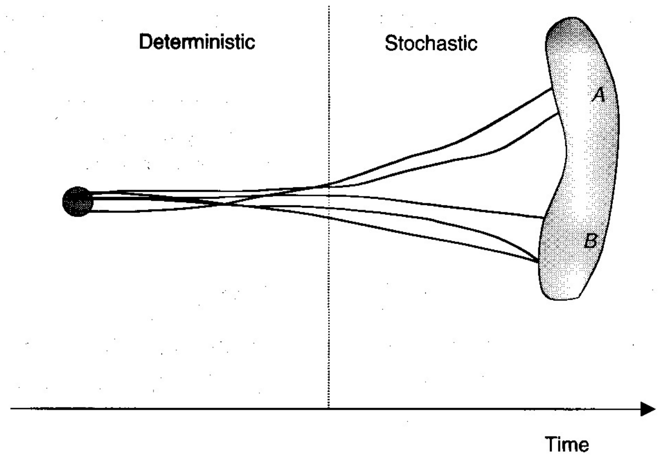
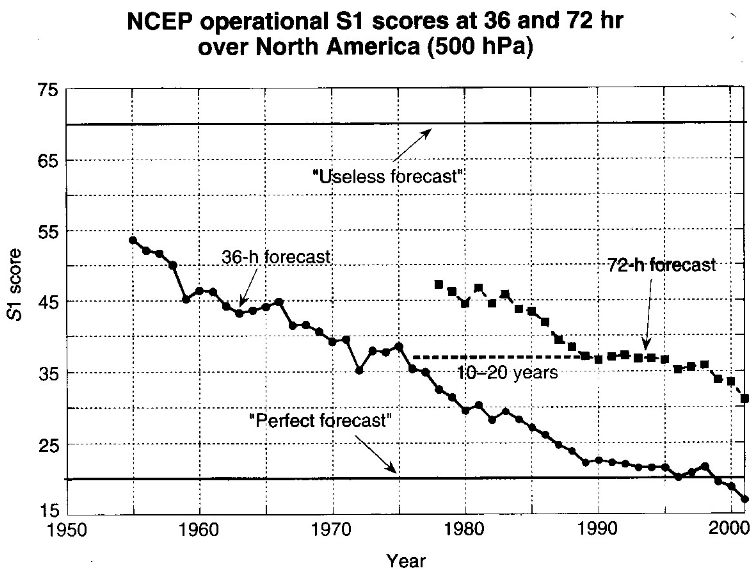
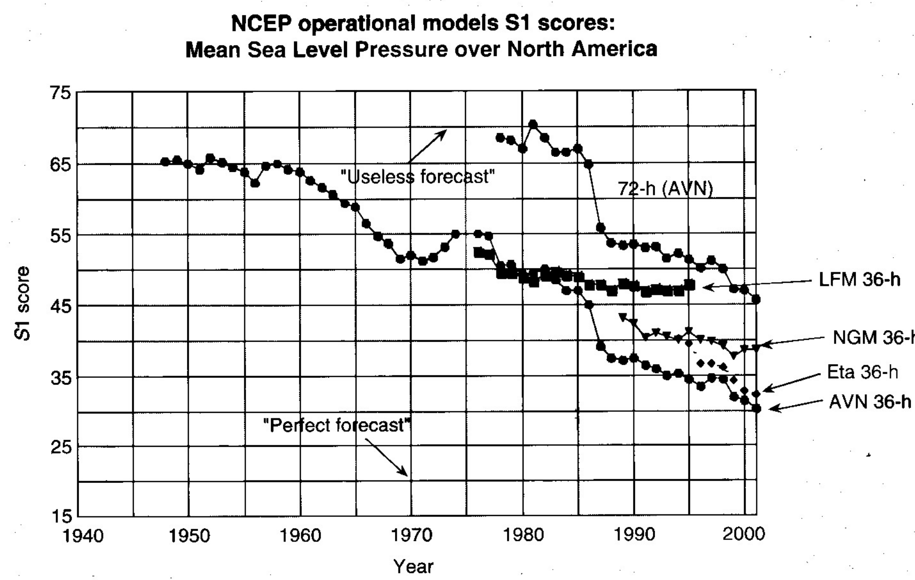


Figure 6.4.1: Schematic of ensemble prediction, with individual trajectories drawn for forecasts starting from a representative set of perturbed initial conditions within a circle representing the uncertainty of the initial conditions (ideally the analysis error covariance) and ending within the range of possible solutions. For the shorter range, the forecasts are close to each other, and they may be considered deterministic, but beyond a certain time, the equally probable forecasts are so different that they must be considered stochastic. The transition time is of the order of 2–3 days for the prediction of large-scale flow, but can be as short as a few hours for mesoscale phenomena like the prediction of individual storms. The transition time is shorter for strongly nonlinear parameters: even for large-scale flow, precipitation forecasts show significant divergence faster than the 500-hPa fields. The forecasts may be clustered into subsets A and B. (Adapted from Tracton and Kalnay, 1993.)

[From Kalnay, 2003]



(a)



(b)

Figure 1.1.1: (a) Historic evolution of the operational forecast skill of the NCEP (formerly NMC) models over North America (500 hPa). The $S1$ score measures the relative error in the horizontal pressure gradient, averaged over the region of interest. The values $S1 = 70\%$ and $S1 = 20\%$ were empirically determined to correspond respectively to a "useless" and a "perfect" forecast when the score was designed. Note that the 72-h forecasts are currently as skillful as the 36-h were 10–20 years ago (data courtesy C.Vlcek, NCEP). (b) Same as (a) but showing $S1$ scores for sea level pressure forecasts over North America (data courtesy C.Vlcek, NCEP). It shows results from global (AVN) and regional (LFM, NGM and Eta) forecasts. The LFM model development was "frozen" in 1986 and the NGM was frozen in 1991.

[From Kalnay, 2003]

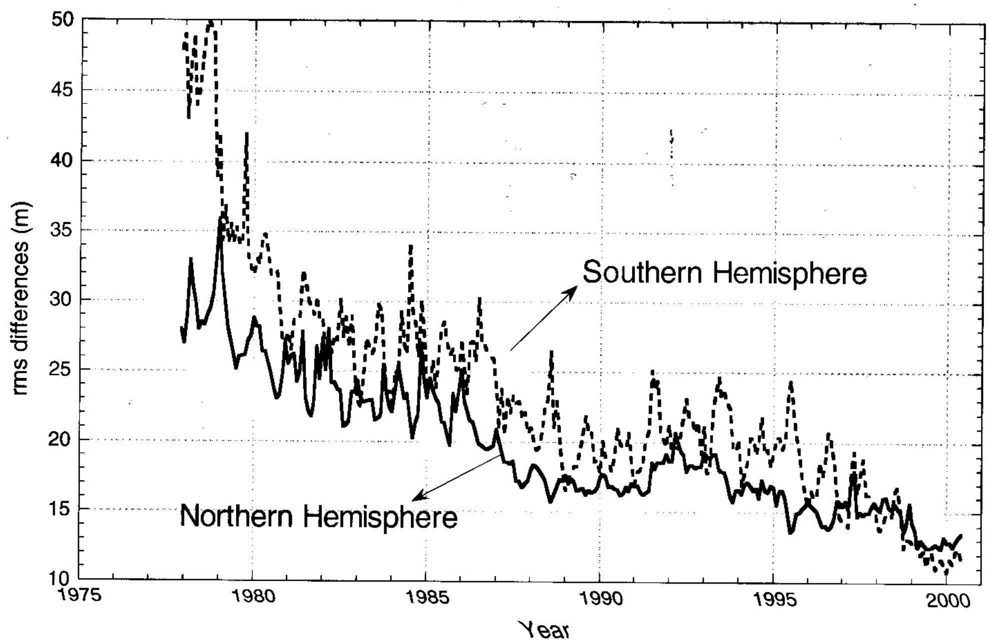
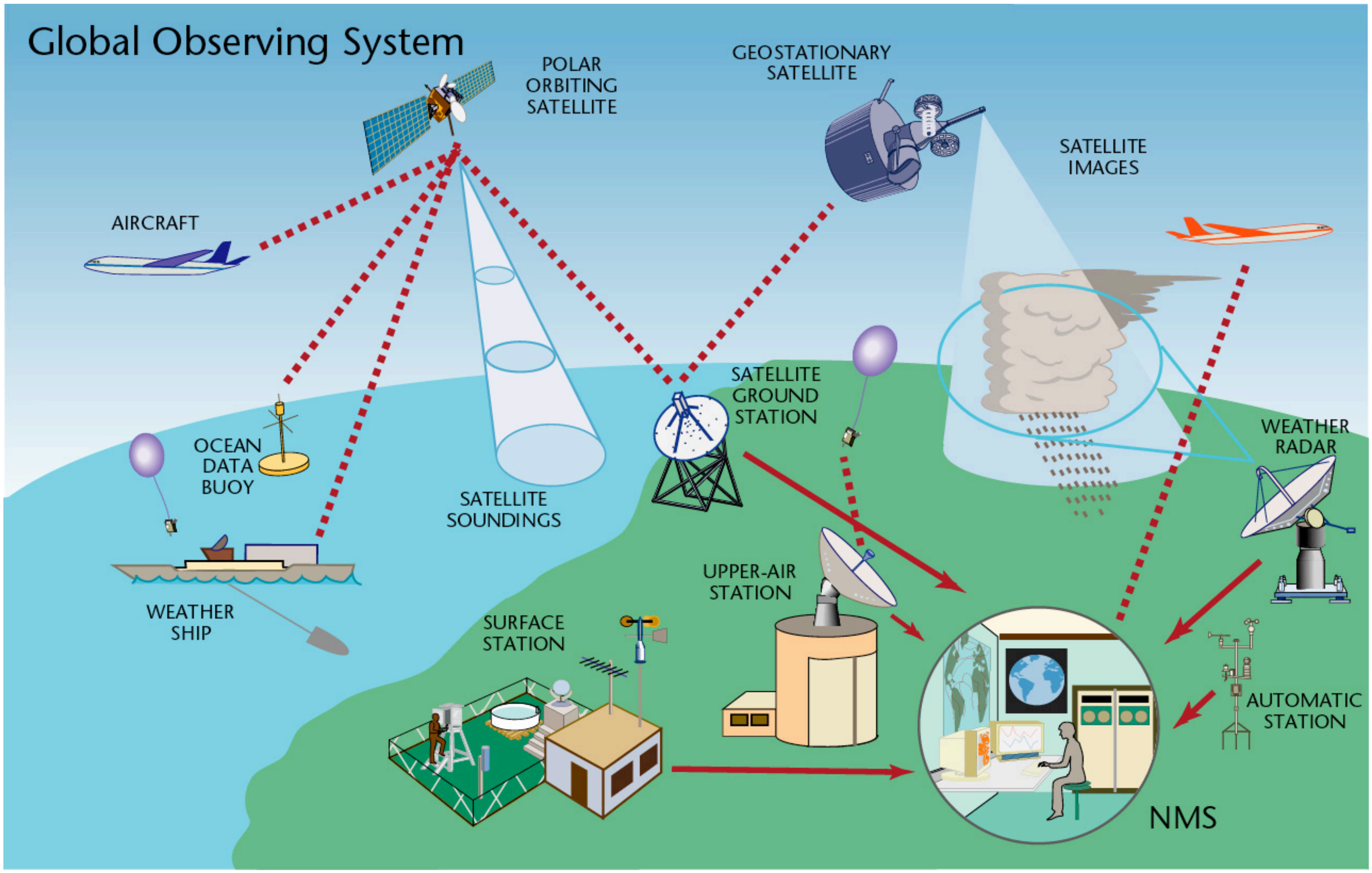


Figure 1.4.3: Rms observational increments (differences between 6-h forecast and rawinsonde observations) for 500-hPa heights (data courtesy of Steve Lilly, NCEP).

[From Kalnay, 2003]

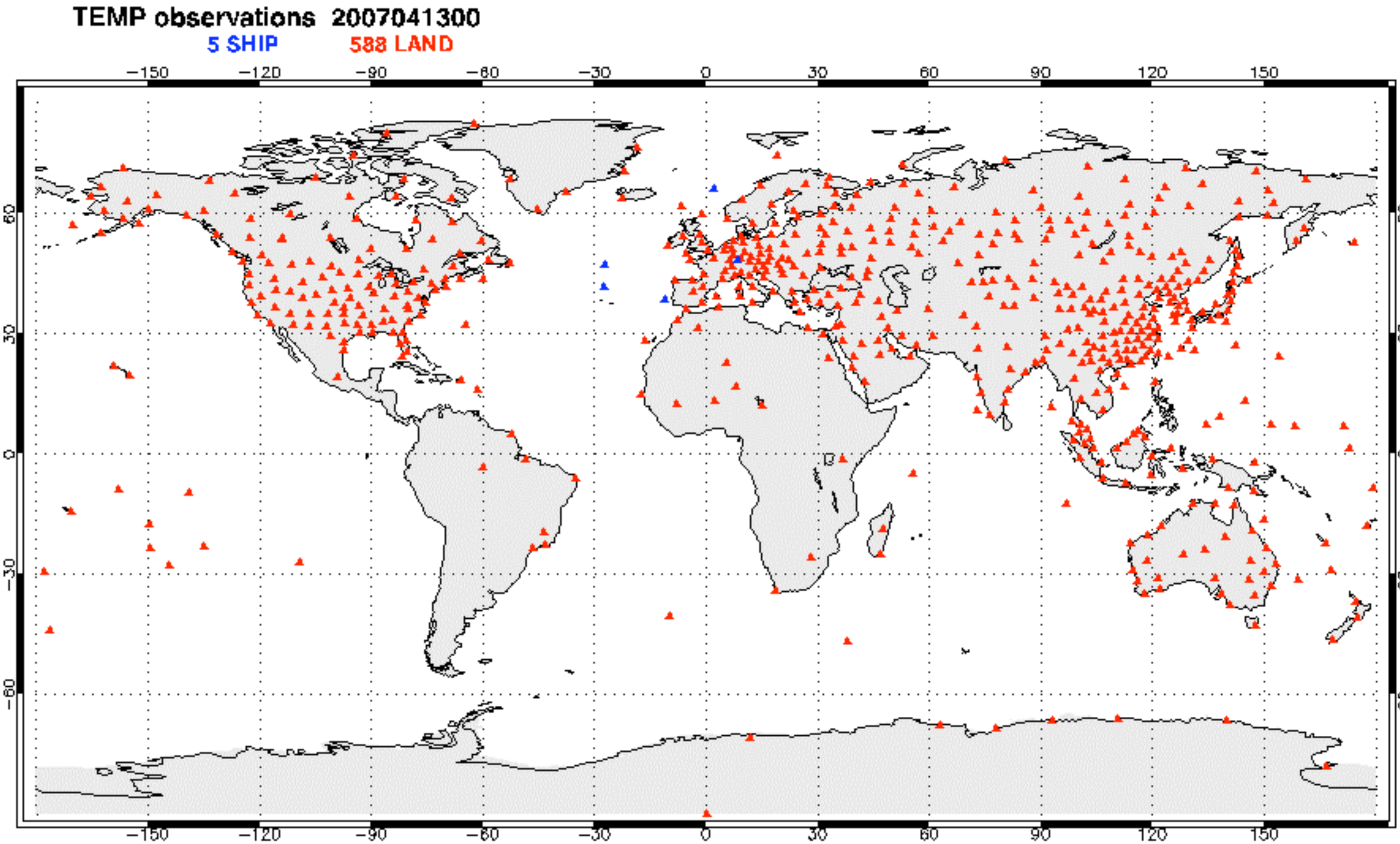
The Global Observing System



http://www.wmo.ch/web/www/OSY/GOS.html

[From Saroja Polavarapu]

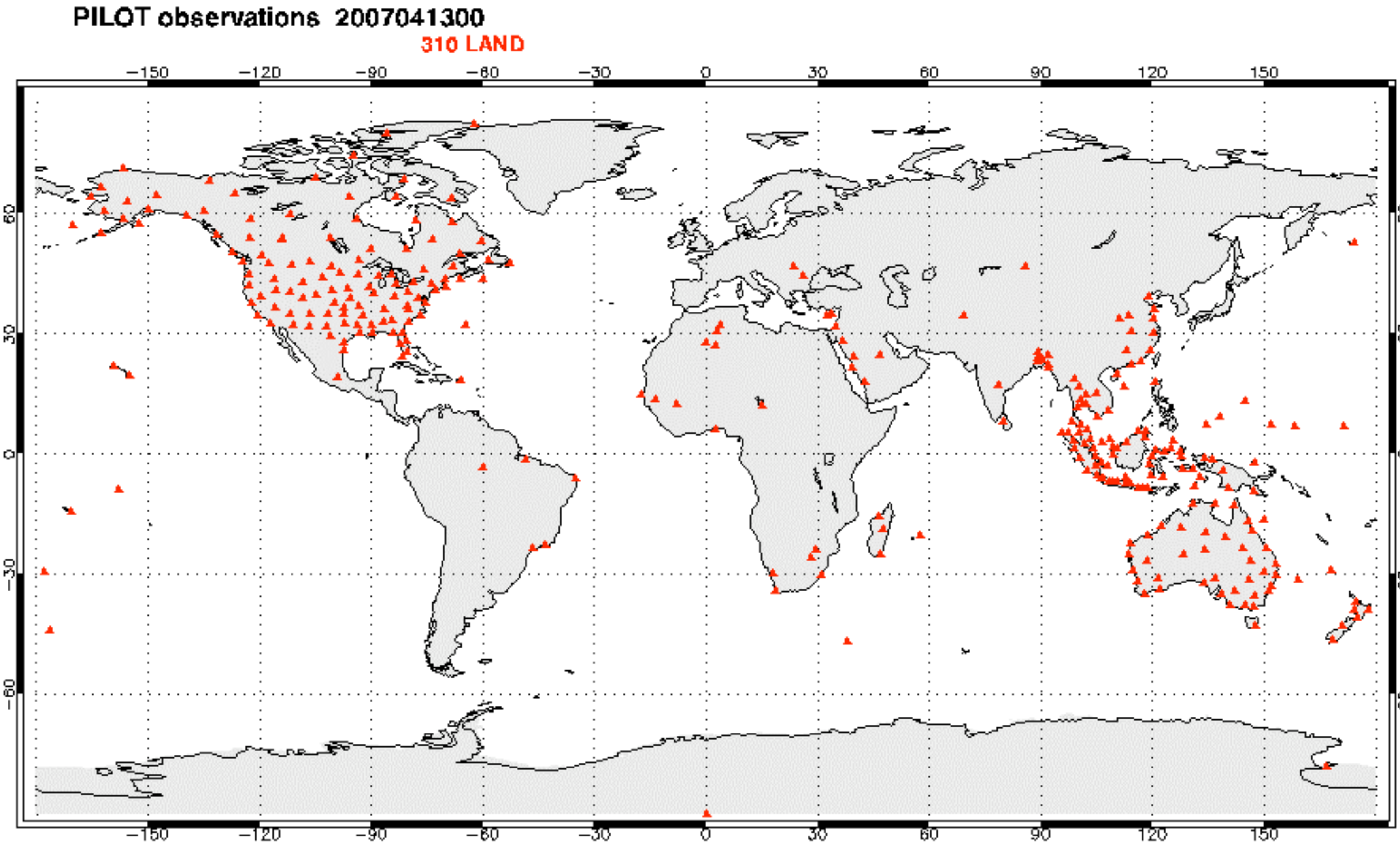
Radiosonde observations used



U,V,T,P,ES profiles at 27 levels

[From Saroja Polavarapu]

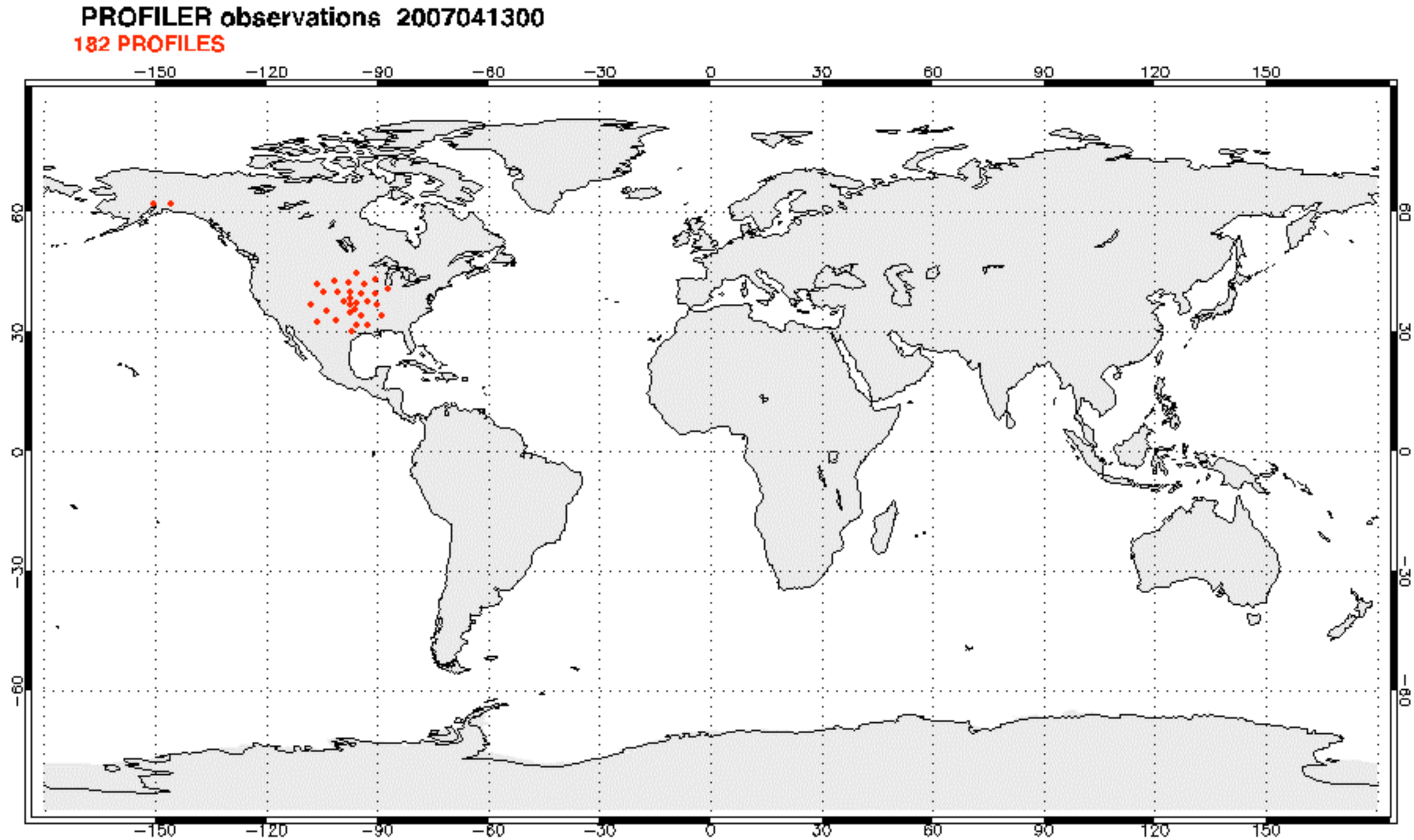
Pilot balloon observations used



U,V profiles at 15 levels

[From Saroja Polavarapu]

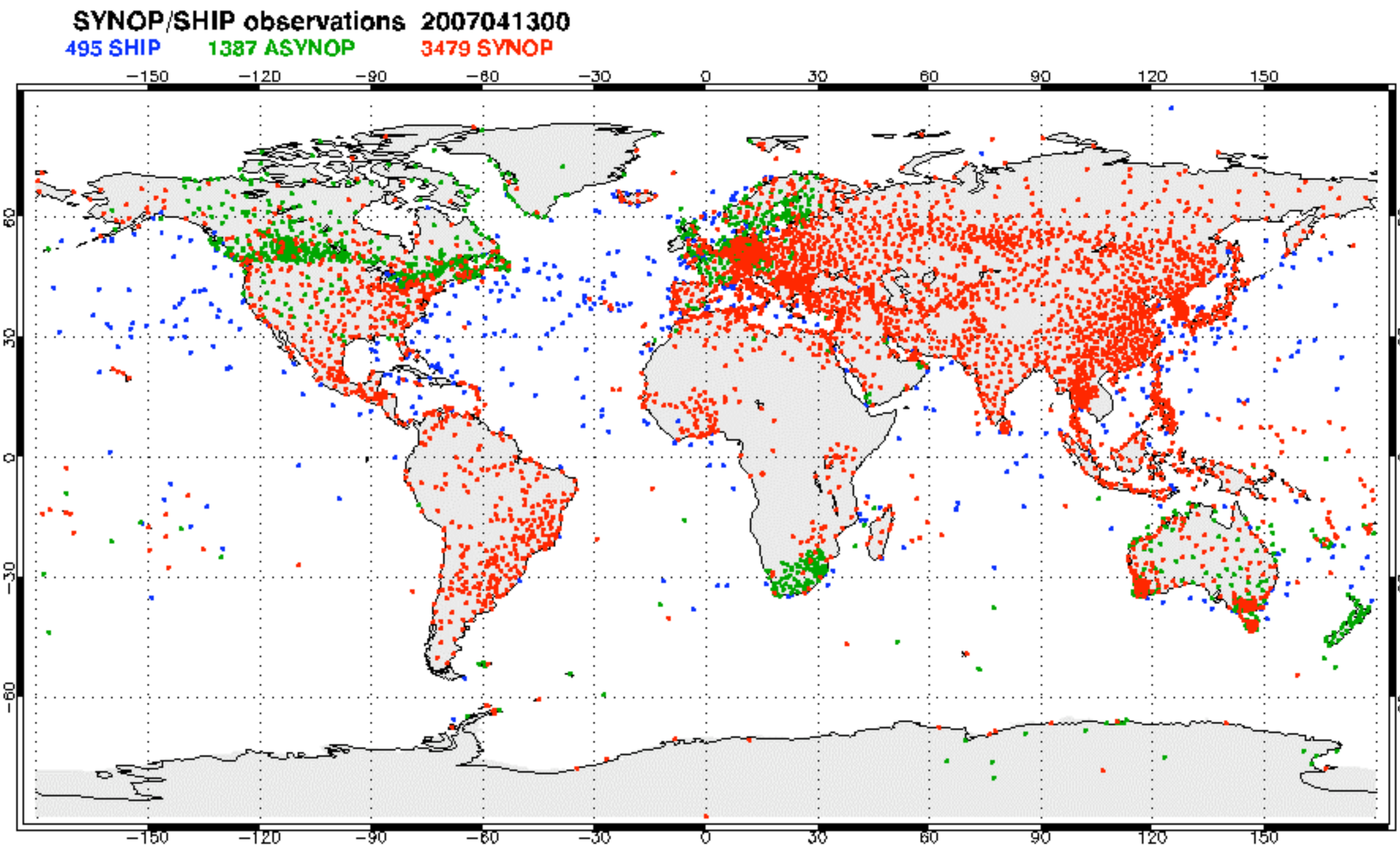
Wind profiler obs used



U,V (speed, dir) profiles at 20 levels

[From Saroja Polavarapu]

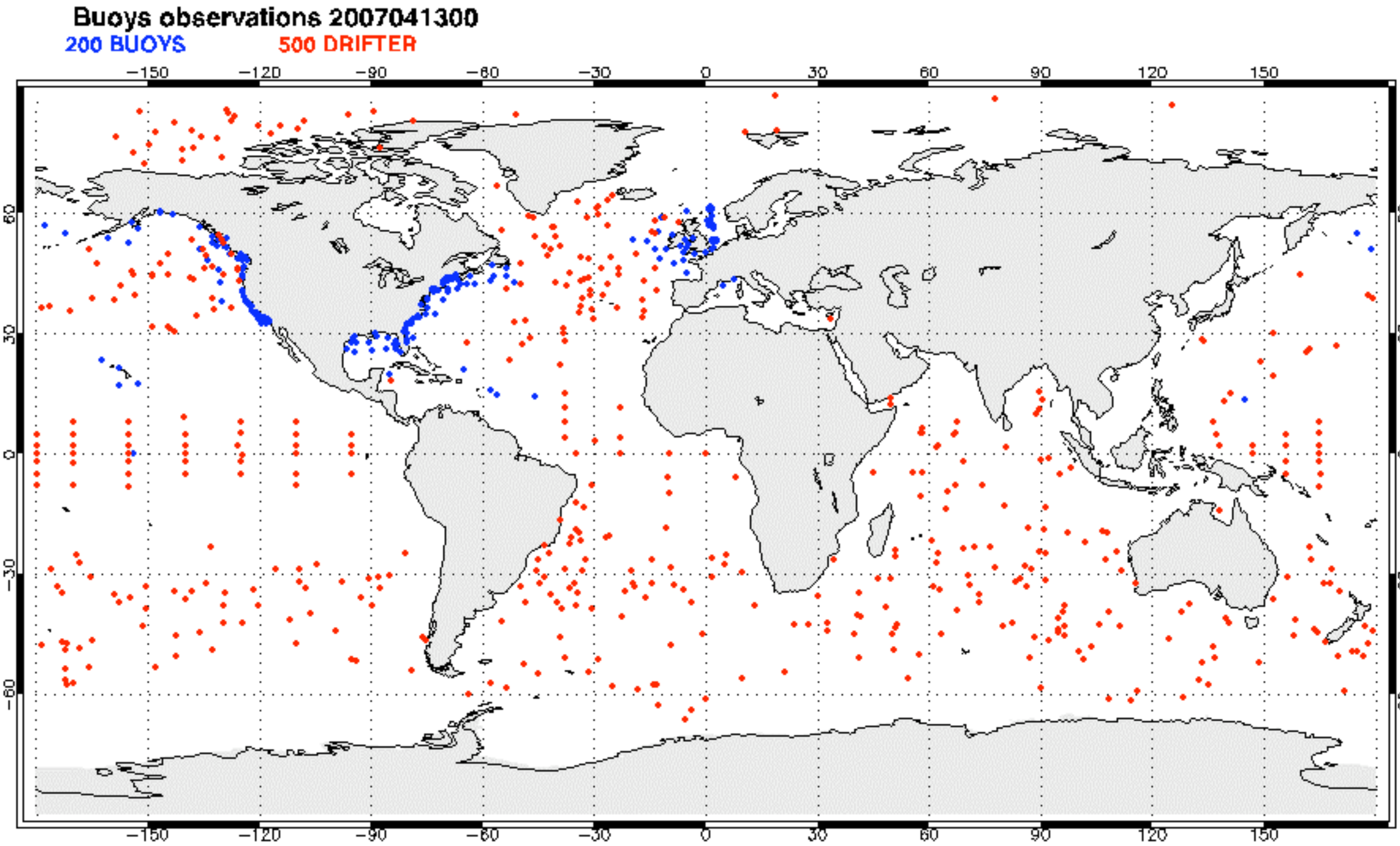
SYNOP and SHIP obs used



U,V,T,P,ES at surface

[From Saroja Polavarapu]

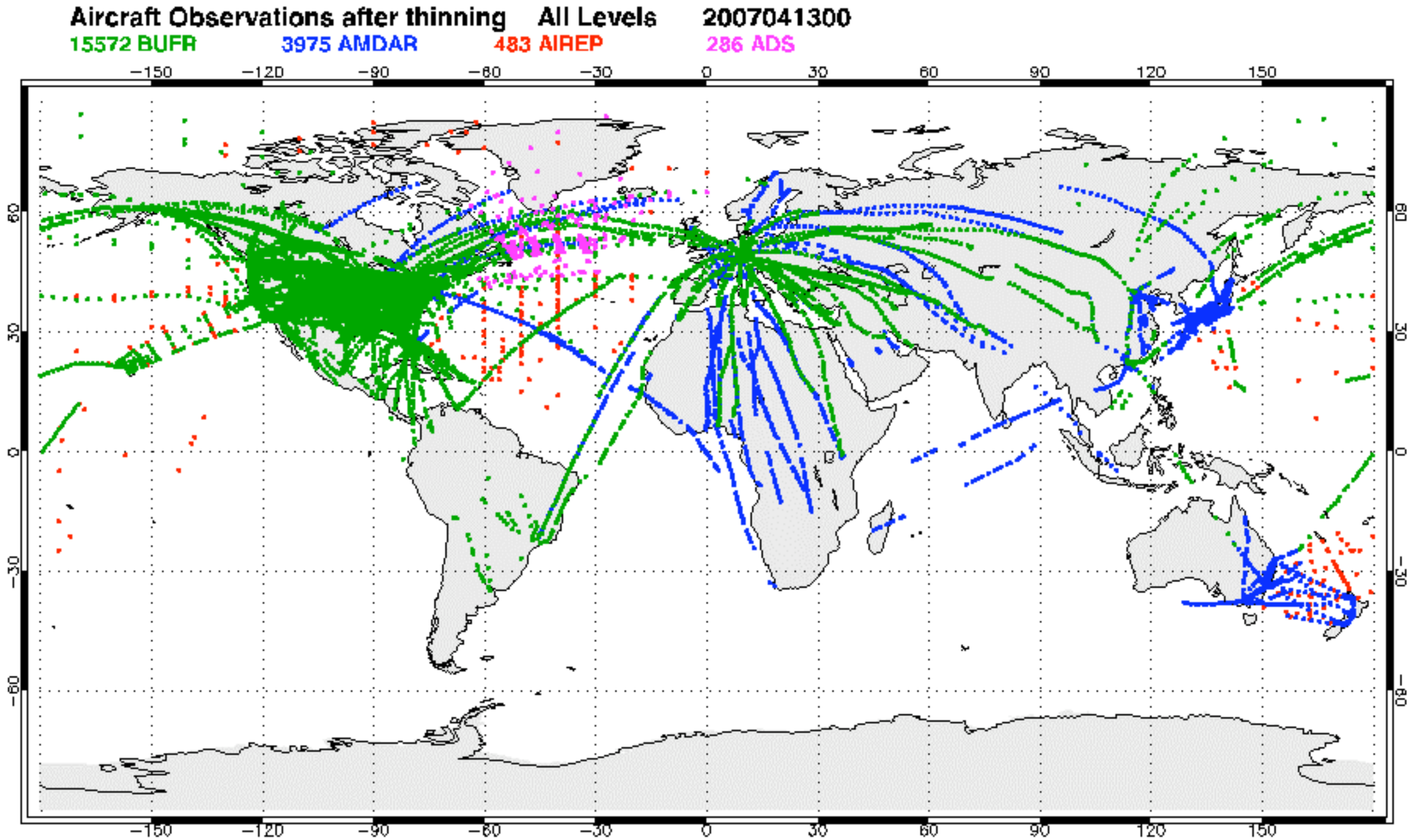
Buoy observations used



U,V,T,P,ES at surface

[From Saroja Polavarapu]

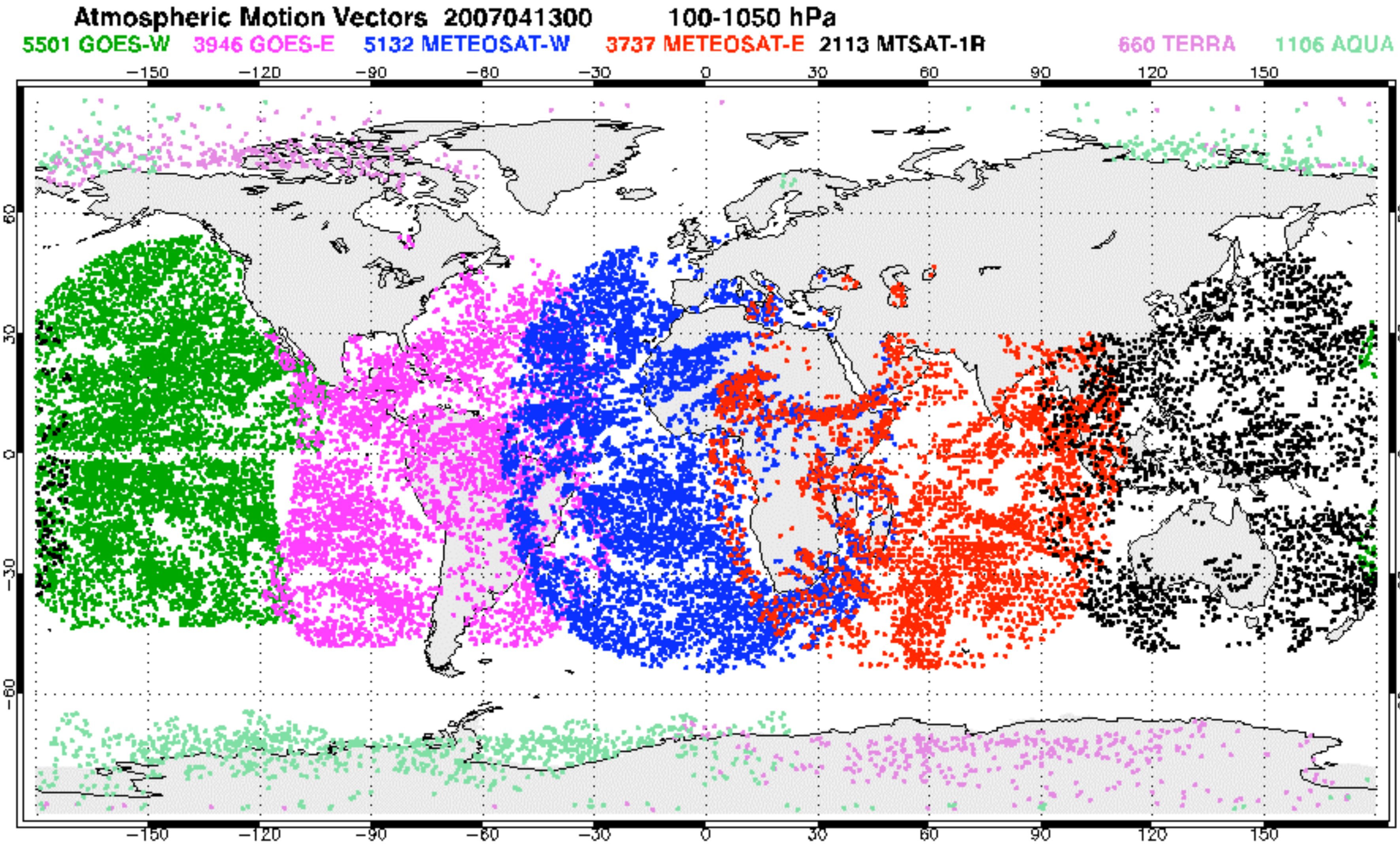
Aircraft observations used



T,U,V single level (AIREP,ADS) or up to 18 levels (BUFR,AMDAR)

[From Saroja Polavarapu]

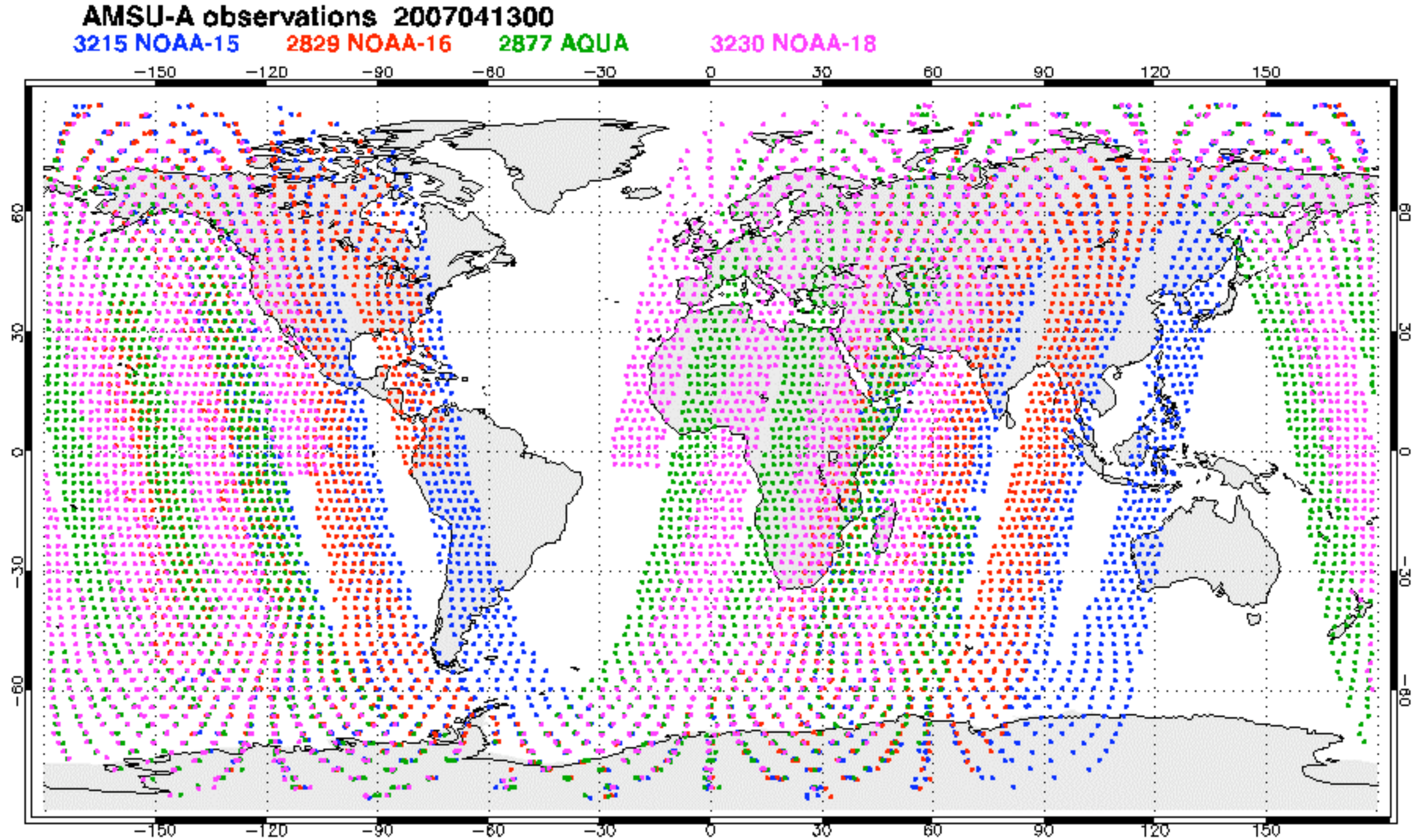
Cloud motion wind obs used



U,V (speed, dir) cloud level

[From Saroja Polavarapu]

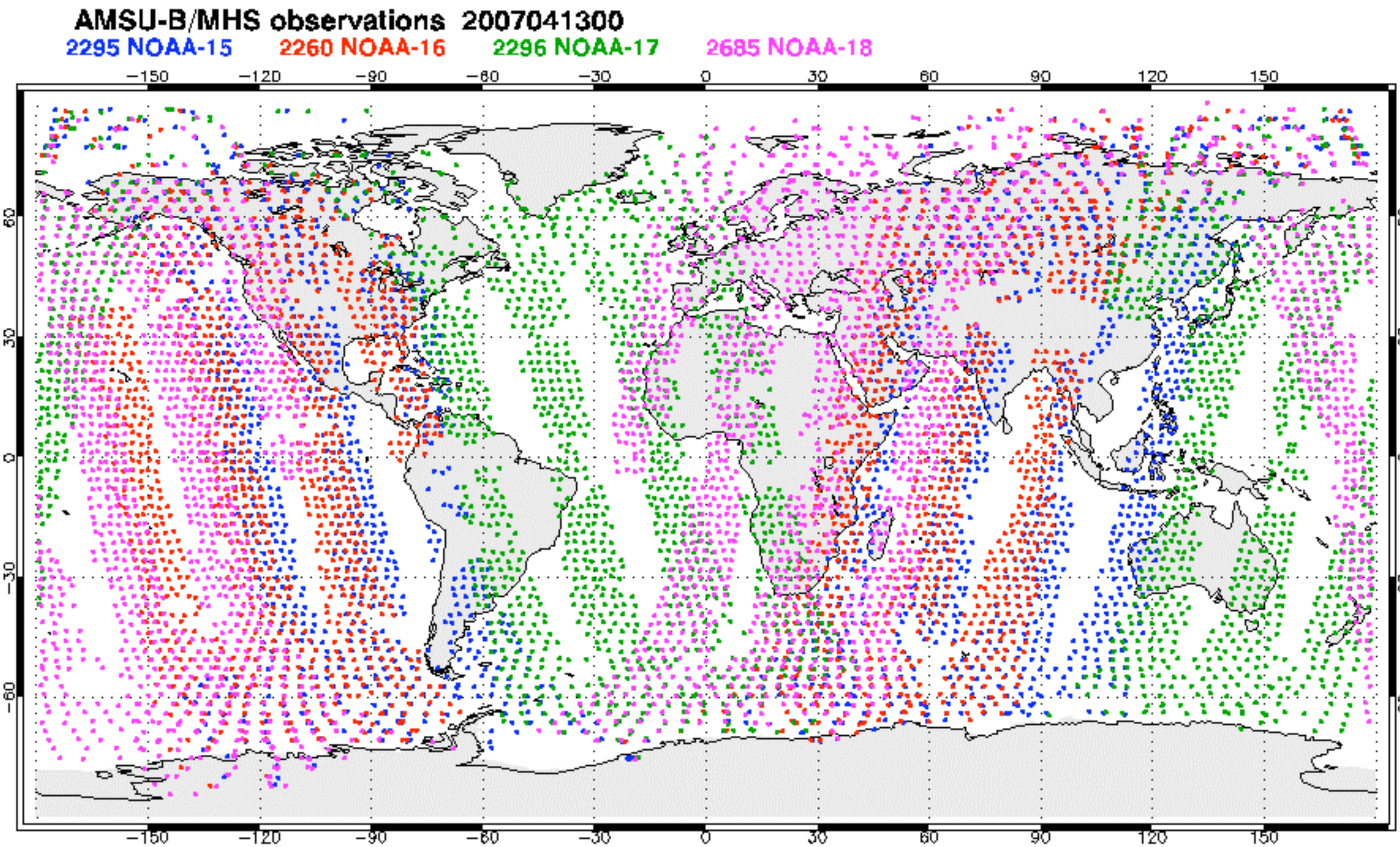
AMSU-A observations used



Brightness temperatures ch. 3-10

[From Saroja Polavarapu]

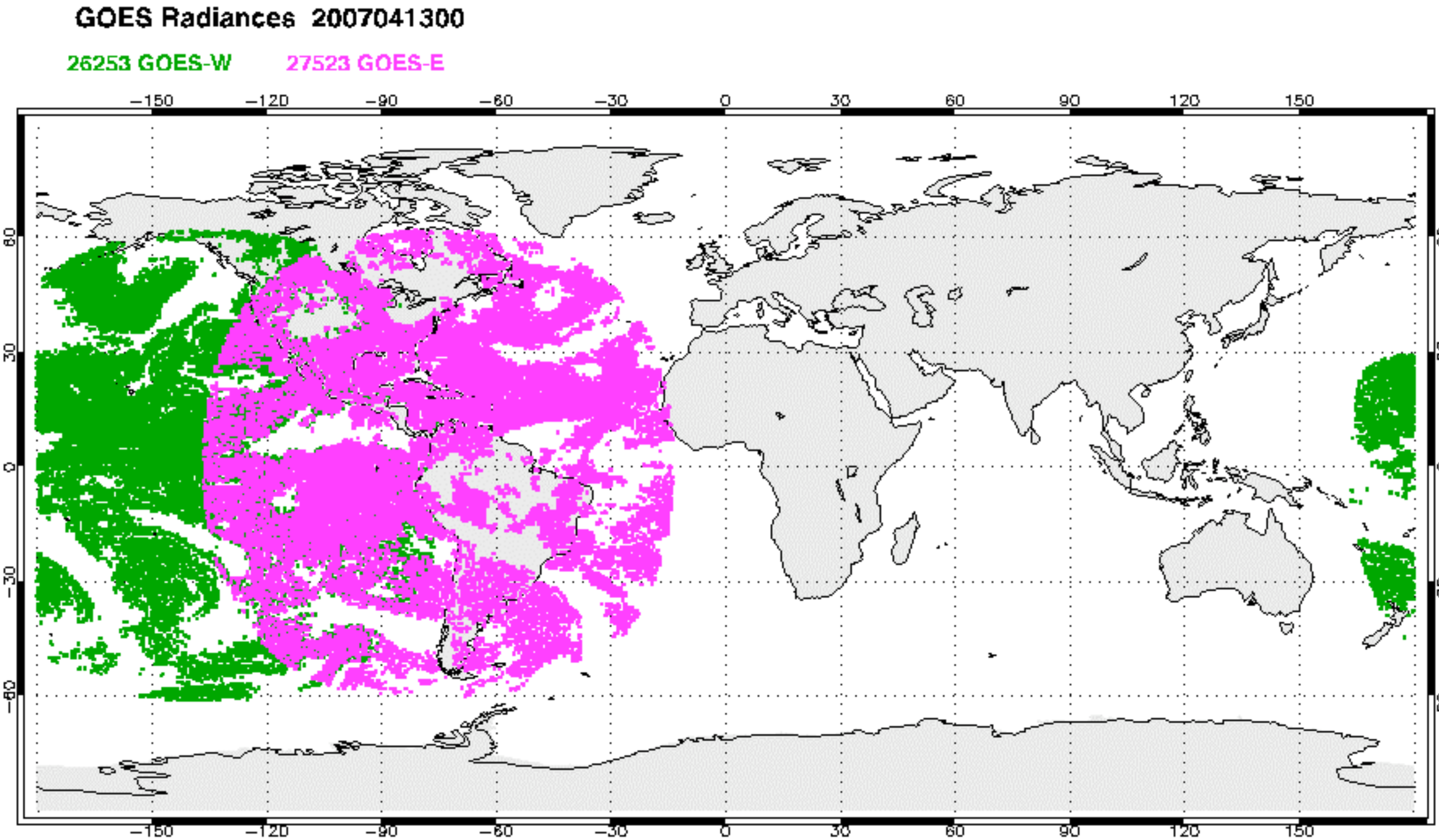
AMSU-B observations used



Brightness temperatures ch. 2-5

[From Saroja Polavarapu]

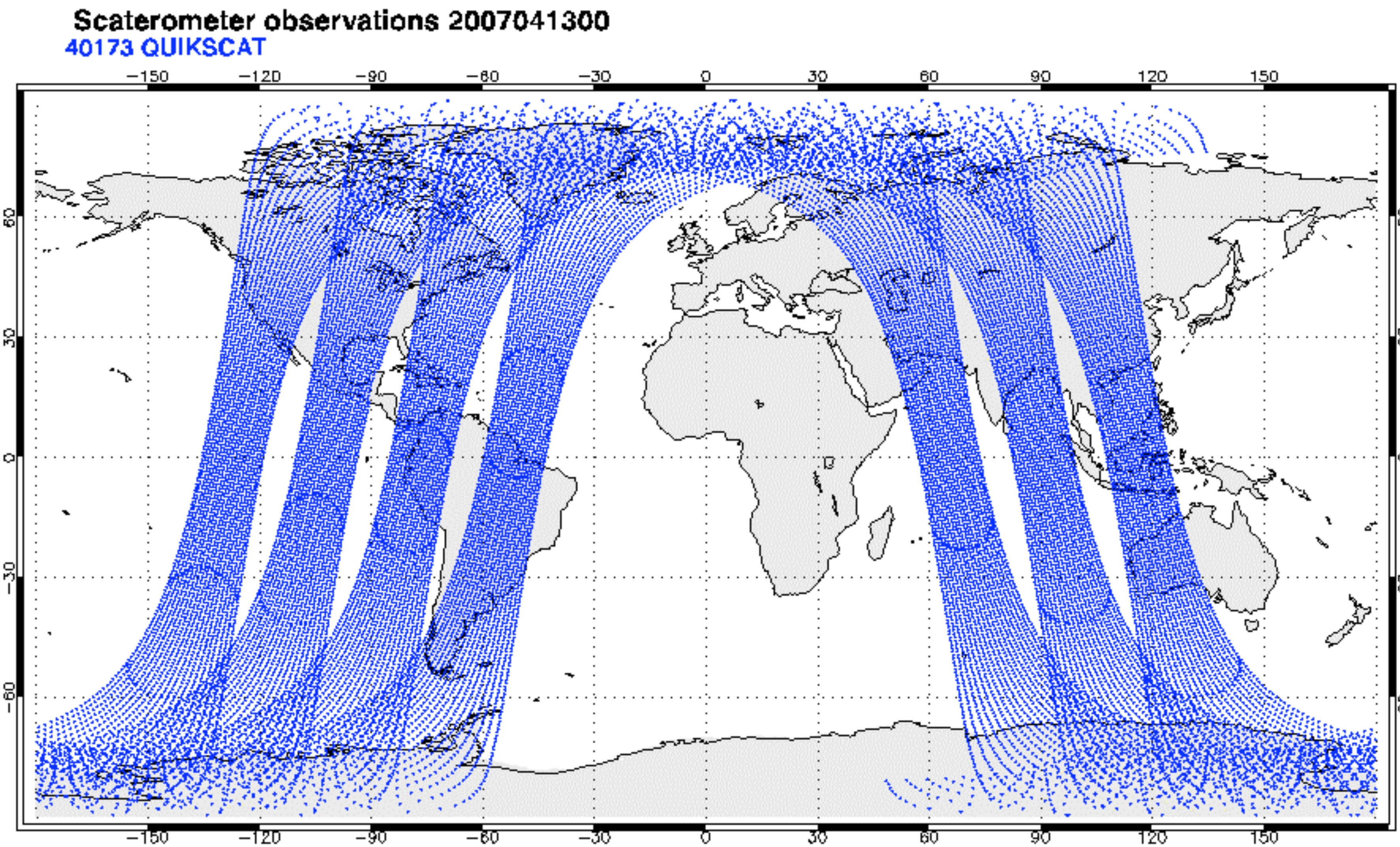
GOES radiances received



Brightness temperature 1 vis, 4 IR

[From Saroja Polavarapu]

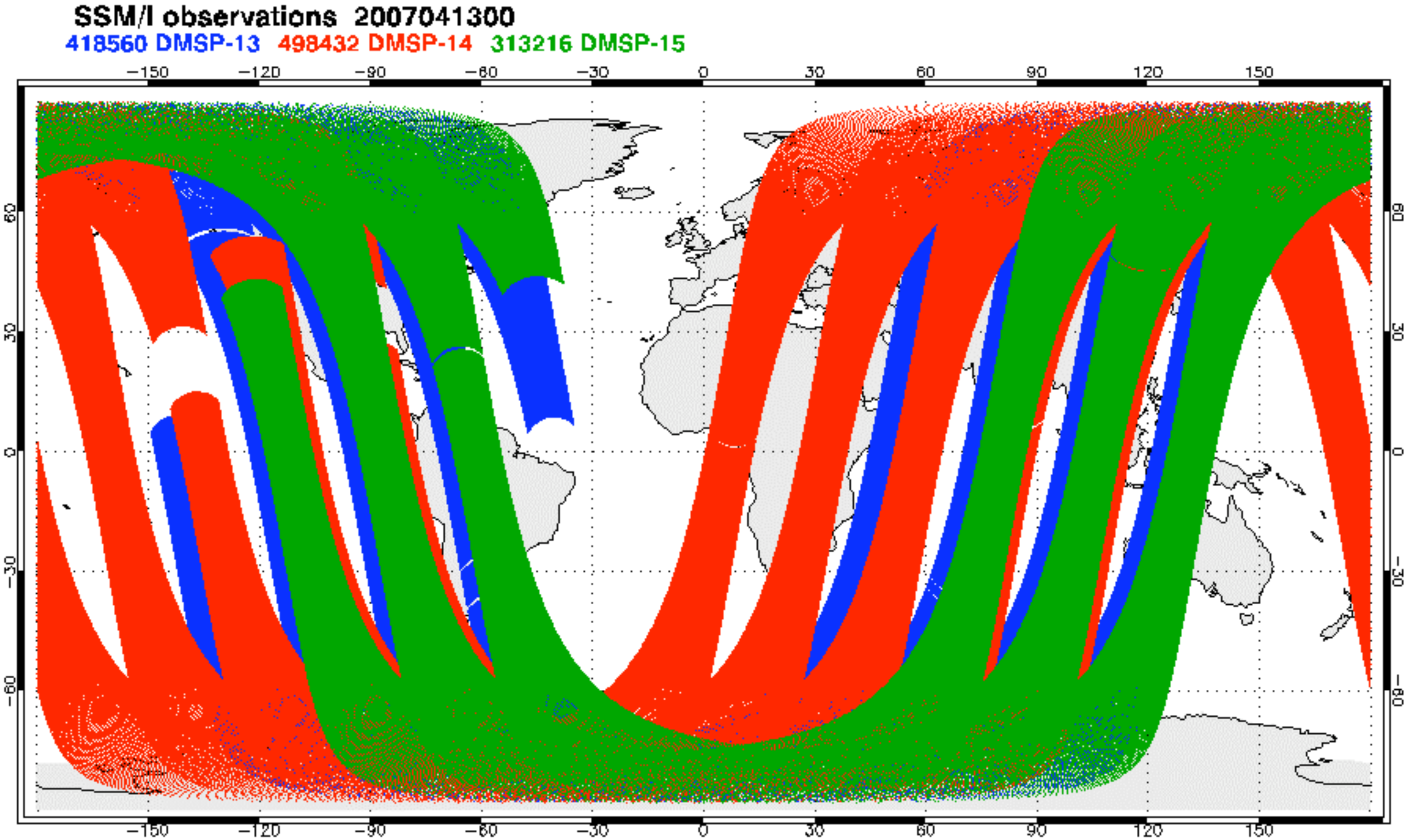
Quikscat received



U,V surface

[From Saroja Polavarapu]

SSM/I observations received



Related to integrated water vapour, sfc wind speed, cloud liquid water

[From Saroja Polavarapu]

Mission Profile 1997 - 2004 • Acronym List

ACRIMSAT
- ACRIM3 - Active Cavity Radiometer Irradiance Monitor

ADEOS II (Midori II)
- AMSR - Advanced Microwave Scanning Radiometer
- GLI - Global Imager
- ILAS-2 - Improved Limb Atmospheric Spectrometer 2
- POLDER - Polarization and Directionality of the Earth's Reflectances

Aqua
- AIRS - Atmospheric Infrared Sounder
- AMSU-A - Advanced Microwave Sounding Unit-A
- CERES - Clouds and the Earth's Radiant Energy System
- MODIS - Moderate Resolution Imaging Spectroradiometer
- HSB - Humidity Sounder for Brazil
- AMSR-E - Advanced Microwave Scanning Radiometer for EOS

Aura
- HIRDLS - High Resolution Dynamics Limb Sounder
- MLS - Microwave Limb Sounder
- OMI - Ozone Monitoring Instrument
- TES - Tropospheric Emission Spectrometer

ESSP/GRACE
Earth System Science Pathfinder/Gravity Recovery And Climate Experiment

- GPS - Black-Jack Global Positioning System Receiver
- HAIRS - High-Accuracy Inter-satellite Ranging System
- SCA - Star Camera Assembly
- SSA - SuperStar Accelerometer
- USO - Ultra Stable Oscillator

ICESat
- GLAS - Geoscience Laser Altimeter System
- GPS - Global Positioning System

Jason-1
- JMR - Jason Microwave Radiometer
- TRSR - Turbo Rogue Space Receiver
- LRA - Laser Retroreflector Array
- DORIS - Doppler Orbitography and Radiopositioning Integrated by Satellite
- Poseidon-2 Altimeter

Landsat 7
- ETM+ - Enhanced Thematic Mapper Plus

METEOR 3M/SAGE III
- SAGE III - Stratospheric Aerosol and Gas Experiment III

NMP/EO-1
New Millennium Program/Earth Observing-1

- ALI - Advanced Land Imager
- Hyperion - Hyperspectral Instrument
- LAC - Linear Etalon Imaging Spectral Array (LEISA) Atmospheric Corrector

OrbView-2
- SeaWiFS - Sea-viewing Wide Field-of-view Sensor

PARASOL
Polarization & Anisotropy of Reflectances for Atmospheric Sciences coupled with Observations for a Lidar

- POLDER - Polarization and Directionality of the Earth's Reflectance

QuikScat
Quick Scatterometer

- SeaWinds

QuikTOMS
- TOMS - Total Ozone Mapping Spectrometer

SORCE
Solar Radiation and Climate Experiment

- TIM - Total Irradiance Monitor
- SIM - Spectral Irradiance Monitor
- SOLSTICE - Solar Stellar Irradiance Comparison Experiment
- XPS - XUV Photometer System

Terra
- ASTER - Advanced Spaceborne Thermal Emission and Reflection Radiometer
- CERES - Clouds and the Earth's Radiant Energy System
- MISR - Multi-angle Imaging Spectroradiometer
- MODIS - Moderate Resolution Imaging Spectroradiometer
- MOPITT - Measurements of Pollution in the Troposphere

TRMM

Tropical Rainfall Measuring Mission

- CERES - Clouds and the Earth's Radiant Energy System
- LIS - Lightning Imaging Sensor
- VIRS - Visible and Infrared Scanner
- TMI - TRMM Microwave Imager
- PR - Precipitation Radar

Mission Profile 2005 - 2015 • *Acronym List*

CATS
Cloud-Aerosol Transport System
- LIDAR

ESSP/Aquarius
- LBR - L-Band Radiometer
- LBS - L-Band Scatterometer

ESSP/CALIPSO
Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations
- CALIOP - Cloud Aerosol Lidar with Orthogonal Polarization
- IIR - Imaging Infrared Radiometer
- WFC - Wide Field Camera

ESSP/Cloudsat
- CPR - Cloud Profiling Radar

ESSP/OCO-2 (also ESSP/OCO)
Orbiting Carbon Observatory
- Three high-resolution grating spectrometers

GCOM-W1
The Global Change Observation Mission-Water
- AMSR2 - Advanced Microwave Scanning Radiometer

Glory
- APS - Aerosol Polarimetry Sensor
- CC - Cloud Camera
- TIM - Total Irradiance Monitor

GPM Core Observatory
Global Precipitation Measurement
- DPR - Dual Frequency Precipitation Radar
- GMI - GPM Microwave Imager

LDCM
Landsat Data Continuity Mission
- OLI - Operational Land Imager
- TIRS - Thermal Infrared Sensor

OSTM
Ocean Surface Topography Mission
- DORIS - Doppler Orbitography and Radio-positioning Integrated by Satellite
- TRSR - Turbo Rogue Space Receiver
- LRA - Laser Retroreflector Array
- Poseidon-3 Altimeter
- AMR - Advanced Microwave Radiometer
- GPSP - Global Positioning System Payload

RapidScat (International Space Station)
- Rapid Scatterometer

Suomi NPP
Suomi National Polar-orbiting Partnership
- ATMS - Advanced Technology Microwave Sounder
- CERES - Clouds and the Earth's Radiant Energy System
- CrIS - Cross-Track Infrared Sounder
- OMPS-Nadir - Ozone Mapping and Profiler Suite
- VIIRS - Visible/Infrared Imager/Radiometer Suite

SAGE-III (International Space Station)
- Stratospheric Aerosol and Gas Experiment - III

SMAP
Soil Moisture Active Passive
- L-Band Radiometer
- L-Band Radar

Mission Profile 2016 - 2023 • *Acronym List*

ACE
Aerosols-Clouds-Ecosystems
- Spectrometer
- Polarimeter
- LIDAR
- Cloud Radar

ASCENDS
Active Sensing of CO_2 Emissions over Nights, Days, and Seasons
- Laser

CLARREO
Climate Absolute Radiance & Refractivity Observatory
- Infrared Spectrometer
- Three Reflected Solar Spectrometers
- GNSS-RO - Global Navigation Satellite Systems - Radio Occultation System

CYGNSS (EV-2)
Cyclone Global Navigation Satellite System (Earth Venture-2)
- 8 micro-satellites using GPS signals to measure ocean surface wind speeds

ESSP/OCO-3 (also ESSP/OCO)
Orbiting Carbon Observatory
- Three high-resolution grating spectrometers

GEO-CAPE
- Ultraviolet-visible-near-infrared
- Infrared imagers

GRACE-FO
Gravity Recovery And Climate Experiment-Follow-on
- GPS - Black-Jack Global Positioning System Receiver
- HAIRS - High-Accuracy Inter-satellite Ranging System
- SCA - Star Camera Assembly
- SSA - SuperStar Accelerometer
- USO - Ultra Stable Oscillator

HyspIRI
- Hyperspectral and thermal infrared imagers

ICESat-2
- ATLAS - Advanced Topographic Laser Altimeter System
- GPS - Global Positioning System

L-Band SAR
- InSAR - Interferometric Synthetic Aperture RADAR (Radio Detection and Ranging)

JPSS 1-2
Joint Polar Satellite System
- ADCS-SARSAT - Advanced Data Collection System/Search and Rescue Satellite-Aided Tracking
- ATMS - Advanced Technology Microwave Sounder
- CERES - Clouds and the Earth's Radiant Energy System
- CrIS - Cross-Track Infrared Sounder
- MIS - Microwave Imager/Sounder
- OMPS-Nadir - Ozone Mapping and Profiler Suite
- SARSAT - Search and Rescue Satellite-Aided Tracking
- SEM-N - Space Environment Monitor-NPOESS
- TSIS - Total and Spectral Solar Irradiance Sensor
- VIIRS - Visible/Infrared Imager/Radiometer Suite

PACE (Pre-ACE)
Pre-Aerosol, Clouds, and ocean Ecosystem
- Ocean color/aerosol spectrometer
- Polarimeter (International partnership TBD)

SWOT
Surface Water Ocean Topography
- Ka-band radar interferometer

TEMPO
Tropospheric Emissions: Monitoring of Pollution
- UV and Visible Offner Grating Sprectrometer

Earth Science Mission Profile 1997 - 2004

Revised: July 1, 2013

Click the mission name below for a detailed description.

1997

OrbView-2 8/1/97
705 km
98.2˚
12:00 PKM
- SeaWiFS

TRMM 11/27/97
402 km
35˚
- CERES
- LIS
- VIRS
- TMI
- *PR* (Japan)

1998

1999

Landsat 7 4/15/99
705 km
98.2˚
10:05 AM
- ETM+

QuikSCAT 6/19/99
803 km
98.6˚
6 AM, 6 PM
- SeaWinds

Antenna ceased rotating in November 2009: still providing useful data through cross-calibration with other satellites.

Terra (AM) 12/18/99
705 km
98.1˚
10:30 AM
- CERES (2)
- MISR
- MODIS
- *ASTER* (Japan)
- *MOPPIT* (Canada)

ACRIMSAT 12/20/99
713 km, 672 km
98.1˚
10:00 AM
- ACRIM3

2000

NMP/EO-1 11/21/00
705 km
98.2˚
10:01 AM
- ALI
- Hyperion
- LAC

2001

QuikTOMS 9/21/01
800 km
97.3˚
10:30 AM
- TOMS

Jason-1 (France) 12/7/01
1336 km
66˚
- JMR
- TRSR
- LRA
- *Poseidon 2*
- *DORIS* (France)

METEOR 3M 3M/SAGE III (Russia) 12/10/01
1020 km
99.5˚
9:30 AM
- SAGE III

2002

ESSP/GRACE (U.S./Germany) 3/17/02
460 km
89˚
- GPS
- HAIRS
- USO
- *SCA* (Denmark)
- *SSA* (France)

Aqua (PM) 5/4/02
705 km
98.2˚
1:30 PM
- AIRS
- AMSU-A
- CERES (2)
- MODIS
- *HSB* (Brazil)
- *AMSR-E* (Japan)

ADEOS II *(Midori II) (Japan)* 12/13/02
803 km
98.6˚
10:15 AM
- SeaWinds
- *AMSR*
- *GLI*
- *ILAS-2* (Japan)
- *POLDER* (France)

2003

ICESat 1/12/03
600 km
94˚
- GLAS
- GPS

SORCE 1/25/03
640 km
40˚
- TIM
- SIM
- SOLSTICE
- XPS

2004

Aura (CHEM) 7/15/04
705 km
98.2˚
1:45 PM
- MLS
- TES
- HIRDLS (UK/US)
- *OMI* (Netherlands/Finland)

PARASOL (France) 12/04
705 km
98.0˚
1:30 PM
- *POLDER* (France)

PARASOL left the A-Train constellation on 12/2/09

Spacecraft not provided by NASA

No NASA contribution (A-Train constellation member)

Currently in Operation

Future Mission

Launch Failure

No Longer in Science Operation

Items in italics not funded by NASA.

[1] OrbView -2 is not provided or operated by NASA but is a data buy.

Earth Science Mission Profile 2005 - 2015

Revised: September 5, 2013

NASA

Click the mission name below for a detailed description.

2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011

ESSP/CloudSat
4/27/06
705 km
98.2°
1:30 PM
- CPR *(US/Canada)*

ESSP/CALIPSO
(France)
4/27/06
705 km
98.2°
1:30 PM
- CALIOP
- WFC
- IIR *(France)*

OSTM
(France)
6/20/08
1336 km
66°
- AMR
- GPSP
- LRA
- *Poseidon Altimeter*
- *DORIS* *(France)*

X
ESSP/OCO
2/24/09
705 km
98.2°
1:15 PM
- Three grating spectrometers

X
Glory
3/4/11
705 km
98.2°
1:30 PM
- APS
- CC
- TIM

ESSP/Aquarius
(Argentina)
6/10/11
657 km
98.0°
6:00 AM
- L-band radiometer
- L-band scatterometer

Suomi NPP
10/28/11
824 km
97.1°
1:30 PM
- ATMS
- CERES
- *VIIRS**
- *CrIS**
- *OMPS**

2012 | 2013 | 2014 | 2015

GCOM-W1
(Japan)
05/18/12
705 km
98.0°
1:30 PM
- *AMSR2*

LDCM
02/11/13
705 km
98.2°
10:30 AM
- OLI
- TIRS

CATS
Int. Space Station
early 2014
350 km
51.6°
- LIDAR

GPM Core
02/14
407 km
65°
- GMI
- *DPR* *(Japan)*

RapidScat
Int. Space Station
04/14
350 km
51.6°
- RapidScat

ESSP/OCO-2
07/14
705 km
98.2°
1:15 PM
- Three grating spectrometers

SMAP
10/14
670 km
6 AM, 6 PM
- L-band radiometer
- L-band radar

SAGE-III
Int. Space Station
early 2015
350 km
51.6°
- SAGE-III

Spacecraft not provided by NASA

No NASA contribution (A-Train constellation member)

Currently in Operation

Future Mission

Launch Failure

No Longer in Science Operation

Items in italics not funded by NASA.

** Instrument provided jointly with the Integrated Program Office (IPO)*

Earth Science Mission Profile 2016 - 2023

Revised: July 26, 2013

Click the mission name below for a detailed description.

2016 | 2017 | 2018 | 2019 | 2020 | 2021

GRACE-FO
(U.S./Germany)
08/2016
460 km
89°
- **GPS**
- **HAIRS**
- **USO**
- ***SCA*** *(Denmark)*
- ***SSA*** *(France)*

ICESat-2
12/2016
- **ATLAS**
- **GPS**

CYGNSS (EVM-1)
2016
500 km
35°
- **8 micro-satellites using GPS signals to measure ocean surface wind speeds**

TEMPO (EV-I)
2017
35786 km
- **UV and visible Offner Grating spectrometer**

JPSS-1
2017
833 km
98.7°
1:30 PM
- **A-DCS***
- **ATMS***
- **CERES***
- **CrIS***
- **OMPS-Nadir***
- **SARSAT***
- **SEM-N***
- **VIIRS***

ESSP/OCO-3
2017
Mission of Opportunity
- **Three grating spectrometers**

SWOT
2020
- **Ka-band radar interferometer**

PACE
2020
- **Ocean color spectrometer**
- **Polarimeter (TBD)**

2022 | 2023

ASCENDS
>2021
- **Laser**

ACE
>2021
- **Spectrometer**
- **Polarimeter**
- **LIDAR**
- **Cloud Radar**

GEO-CAPE
>2021
- **UV-Vis-NIR**
- **IR imagers**

HyspIRI
>2021
- **Hyperspectral and TIR imagers**

L-Band SAR
>2021
- **InSAR**

CLARREO
>2023
609 km
90°
- **Infrared and/or Reflected Solar spectrometer**
- **GNSS-RO**

JPSS-2
833 km
98.7°
1:30 PM
- **A-DCS***
- **ATMS***
- **CERES***
- **CrIS***
- **OMPS-Nadir***
- **SARSAT***
- **SEM-N***
- **TSIS***
- **VIIRS***

Spacecraft not provided by NASA

No NASA contribution (A-Train constellation member)

Currently in Operation

Future Mission

Launch Failure

No Longer in Science Operation

Items in italics not funded by NASA.

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