Validating the Past

Simulating the Weather in Space Mission Earth Views

Adapted from "Forecasting the Past: Views of Earth from the Moon and Beyond," by **Philippe Lopez** (European Centre for Medium-Range Weather Forecasts). Published online in BAMS, July 2020. For the full, citable article, see [DOI:10.1175/BAMS-D-19-0254.1](https://doi.org/10.1175/BAMS-D-19-0254.1).

Celebrations of the fiftieth anniversary of the Apollo missions (1968–72) included worldwide distribution of several iconic photos of Earth taken from the moon. At the time, images of Earth from space were still new: the meteorological satellite program was just beginning. Since then much progress has been made observationally, spanning images provided by the first geostationary satellite *ATS-1* in 1966 to today's high-spatial- and high-temporal-resolution images from the latest geostationary satellites. Better and more numerous satellite

✦ A few of the many photographs taken from the lunar surface by the *Apollo 17* astronauts featured Earth in their background, such as this one (a) taken by Gene Cernan at 0216 UTC 13 Dec 1972. (b) We zoomed in and compared with (c) a 9-km resolution 27-h IFS forecast initialized from the ERA5 reanalysis. Most cloud features seen on the *Apollo 17* photograph taken from the lunar surface seem to have an equivalent in the simulated image, both in the midlatitudes and in the tropics. The fact that some discrepancies can be found in the detail of these cloud structures is not surprising. However, even a tiny image of Earth extracted from a 47-yr-old photograph can still provide a reasonable source of qualitative evaluation for numerical weather prediction.

observations are one important reason our predictions of the behavior of the Earth's atmosphere have improved dramatically since the 1970s. Other main reasons include our constantly improving capability to model atmospheric and surface processes and to extract

information from observations through data assimilation.

We celebrate and document this remarkable improvement in numerical weather prediction (NWP) and in reforecasting past weather by making a purely visual validation

At 1039 UTC 7 Dec 1972, the crew of *Apollo 17* captured *► the iconic “Blue Marble” image, (a) 29,000 km away from Earth. Comparison with the corresponding simulated visible image (b) from an 11-h reforecast started from ERA5 reanalysis data valid at 0000 UTC 7 Dec 1972 indicates that most cloud systems south of 30°S are represented fairly realistically. However, a few obvious mismatches can be identified in the tropics and extra-tropics. Forecast (c) over 59 hours, also initialized from ERA5, and (d) over 11 hours initialized from ERA40. The reforecasts for the *Apollo 17* “Blue Marble” case are somewhat degraded from 1990 mainly because only a single polar-orbiting meteorological satellite was assimilated in the ERA5 reanalysis. However, this case also clearly highlights the superiority of ERA5 over ERA-40, due to the larger number of observations assimilated (particularly, no satellites were used in ERA-40) as well as the better modeling/data assimilation system and higher horizontal and vertical resolutions of ERA5.

▲ * (a) NASA's *Apollo 11* Earthrise picture taken from the orbiting command module at around 0500 UTC 20 Jul 1969, just a few hours before Neil Armstrong set foot on the moon. (b) The corresponding simulated image from a 29-km-resolution, 29-h IFS forecast initialized from ERA-40 reanalysis. Note that the portion of the lunar surface seen on the NASA image was copy-pasted on the simulated image. Even though no satellite observations were assimilated in ERA-40 for that day, it is remarkable that many clouds have an equivalent in the simulated image, particularly in the extratropics. Over the tropical Pacific, however, the level of agreement is not as good, due to 1) the lack of observations over oceans in the ERA-40 reanalyses for 1969, and 2) the longstanding challenge of accurately forecasting convective activity, particularly inside the intertropical convergence zone.

of reforecasts using pictures taken by various space missions over the past fifty years. This involves using global atmospheric analyses that were generated using the highest resolution available, the most recent data assimilation system, and up to 30 million

in situ and satellite observations (for recent dates).

The reforecasts use the European Centre for Medium-Range Weather Forecasts (ECMWF)'s Integrated Forecasting System (IFS) initialized from ECMWF's best (re)analyses for each selected date. Running reforecasts ensured the timely comparison of models with the selected photographs and offered the advantage of using the latest version of the forecast model at the highest resolution currently affordable.

Data and methodology

The numerical weather reforecasts discussed here were run using the latest operational version of the IFS at the current global resolution of 9 km with 137 vertical levels to obtain the most detailed representation of clouds possible. The global reanalyses used for forecast initialization were from ECMWF's ERA5 (Copernicus Climate Change Service) for dates after 1972 and ERA-40 for earlier dates. More observations have generally been assimilated in ERA5 than in ERA-40 for any date common to both reanalysis datasets, with the added benefits of higher resolution and superior data assimilation system.

A computationally inexpensive visible image simulator that primarily relies on hourly averaged top-of-the-atmosphere solar fluxes forecast by the

◀* (column a) Four images of Earth taken by NASA's *Galileo* spacecraft on its first flyby, at between 2 and 2.7 million km from Earth on 11 and 12 Dec 1990. (column b) Corresponding simulated images from a 9-km-resolution IFS forecast initialized at 0000 UTC 11 Dec 1990 from ERA5 reanalysis. The visual agreement between the simulated and *Galileo* images is quite striking, even in the tropics. This resemblance reflects good performance of the forecast model and the quality of the ERA5 global reanalysis for the year 1990. In column (b), forecast ranges are (from top to bottom) 14, 20, 27, and 32 h, to match the time of each *Galileo* image in (a).

IFS was specially developed. More elaborate visible image simulators do exist, though the associated computational cost was prohibitive for this study.

One of the main challenges in this work was obtaining enough reliable information about the exact time and viewing geometry of each picture. In this respect, one advantage of visible over infrared imagery is that the location of the terminator combined with the position of continents can help confirm the time of an image.

Conclusions

This study illustrates that state-of-the-art NWP systems such as the IFS can deliver remarkably accurate cloud forecasts on a global scale for

recent dates. Even cloud simulations for much older dates are realistic, provided the same modern forecasting system initialized from high-quality reanalyses, such as ERA5, is used.

The comparison of simulated and Apollo images can provide validation for global cloud predictions despite remoteness in space and time. Apollo is in fact our best source of cloud validation on the global scale pre-1970. Later, the assimilation of satellite observations has contributed to the significant improvement of reanalyses and reforecasts initialized from them. Amazingly, the progress in NWP of the past decades now allows us to open virtual windows into the past and glimpse at our planet's atmosphere as far back as the 1960s. ♣

≡ METADATA

BAMS: What would you like readers to learn from this article?

Philippe Lopez (European Centre for Medium-Range Weather

Forecasts): *This article offers a visual demonstration that the worldwide, relentless, multifaceted developments in numerical weather prediction over the past decades now allow us to open windows into the distant past to catch virtual glimpses of our planet's atmosphere as far back in time as the 1960s.*

BAMS: How did you become interested in the topic of this article?

PL: *This short study gave me an opportunity to combine my professional interest in meteorology with my lifelong passion for space. In July 2019, old but fascinating photographs of our planet captured from the moon by NASA's Apollo 11 mission were broadcast by the media to celebrate the fiftieth anniversary of the first moon landing. I immediately wondered: Would the ECMWF's Integrated Forecasting System (IFS) be able to simulate realistic views of Earth from that time?*

BAMS: What surprised you the most about the work you document in this article?

PL: *What strikes me the most in this study is that modern global simulations of cloud systems can match so well with corresponding photographs from space even from half a century ago, despite the more limited coverage in observations available back then. This highlights the excellent quality not only of our numerical weather prediction model, but also of the ERA5 reanalyses that I used to initialize my simulations. Less seriously, every time I look at the Earthrise photograph taken by Apollo 11 from the moon on July 20, 1969, I cannot help feeling baffled, if not a little scared, by the idea that I was there too, standing in my playpen, probably crying while Mom and Dad were both glued to their tiny single-channel, black-and-white TV set, watching historical events unfold. And it brings tears to my eyes, but for other reasons than in 1969!*

BAMS: What was the biggest challenge you encountered while doing this work?

PL: *The biggest challenge was to obtain reliable information about the photographs from early space missions, such as their exact date and time as well as their precise viewing geometry. For instance, for an Apollo-13 photograph (not shown in the article), various sources gave me three completely different dates and distances to Earth. Some serious sleuth work was necessary to figure out the correct values. This aspect made me realize the daunting task faced by my colleagues who devote their careers to the production of atmospheric reanalyses of past weather, such as ERA5, and therefore need to recover as many ancient observations as possible. The further into the past, the harder it gets.*

BAMS: What's next?

PL: *Even though this study was totally unplanned and thus supposed to be very short, one of its useful outcomes will be the availability of the offline image simulator, which allows the visual comparison of the model with real-life photographs.*