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Inter-technique comparison of integrated water vapour measurements for climate change analysis

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Abstract

Water vapour plays a dominant role in the climate change debate. However, observing water vapour for a climatological time period in a consistent and homogeneous manner is a challenging task. To this end, water vapour estimations derived from ground-based observations of **Global Navigation Satellite System (GNSS)** receiver networks such as the International GNSS Service (IGS) network are very promising, with continuous observations spanning over the last 15+ years. In addition, the **AErosol RObotic NETwork (AERONET)** also provides long-term and continuous ground-based observations of the total water vapour content performed with standardized and well-calibrated sun photometers.

The present study aims to assess the applicability of either datasets for **water vapour time series analysis**. Therefore, we compare the Integrated Water Vapour (IWV) measurements retrieved (at zenith) from these two techniques, focusing on a selection of almost 30 sites worldwide and we show that **both techniques agree at the level of -0.26 mm ± 1.41 mm of IWV**.

In a case study, we also investigate the **influence of the clouds on the IWV inter-technique comparison**. Therefore, we focus on the station Uccle (Brussels, Belgium) and we compare the IWV values obtained from these instruments directly in the direction of the sun **("solar slant IWV")**.

Finally, for a selection of sites, we **compare** the **GNSS** and **sun photometer** IWV values with simultaneous and co-located **radiosonde** and satellite-based IWV measurements (**GOME/GOME2/SCIAMACHY, IASI**) and we investigate the geographical dependency of the properties of the IWV scatter plots between all these different instruments.

1. Instruments and Datasets

Instruments:

- 2 Ground-Based Instruments
- 1 In-Situ Instrument
- 3 Satellite-Based Instruments

Global Navigation Satellite Systems — Radiosondes — CIMEL Sun photometers — GOME II / SCIAMACHY / IASI

Within a maximum separating distance of 30 km, **28 co-locations** are found **worldwide** between **IGS GNSS** sites and AERONET **CIMEL sun photometer** locations (see Fig. 1). Additionally, we looked for radiosonde launches and GOME(2), SCIAMACHY, IASI crossings at those selected sites. The data availability as a function of time for these different instruments at the 28 co-locations is shown in Fig. 2. The IWV data sets from the different instruments are described below:

- **GNSS**: GPS-based Zenith Total Delay (ZTD) from the IGS Final (re)processing (*Byun and Bar-Sever* [2009,2010]) is converted into IWV (see next section).
- **CIMEL**: IWV is obtained by measuring the (direct) sun radiance at a 940nm channel (centred on the 946nm water vapour absorption line).
- **Radiosondes**: IWV is calculated through integration of the vertical profiles of temperature and relative humidity.
- **GOME(2)/SCIAMACHY**: IWV is retrieved by applying the so-called Air Mass Corrected Differential Optical Absorption Spectroscopy method to nadir measurements around 700nm.
- IASI: IWV retrieval is possible with infrared interferometry. However, the impact of the cloud cover on IASI IWV is still a major issue for us, therefore results are not presented here.

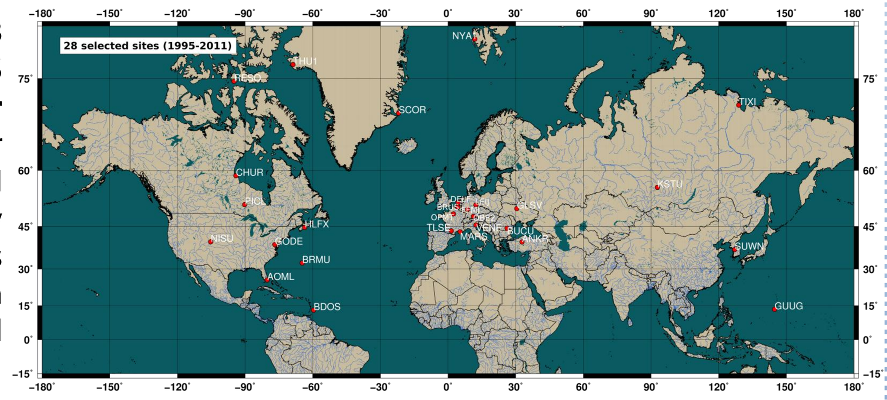


Fig. 1: Map of the selected sites that host at least 2 of the considered instruments.

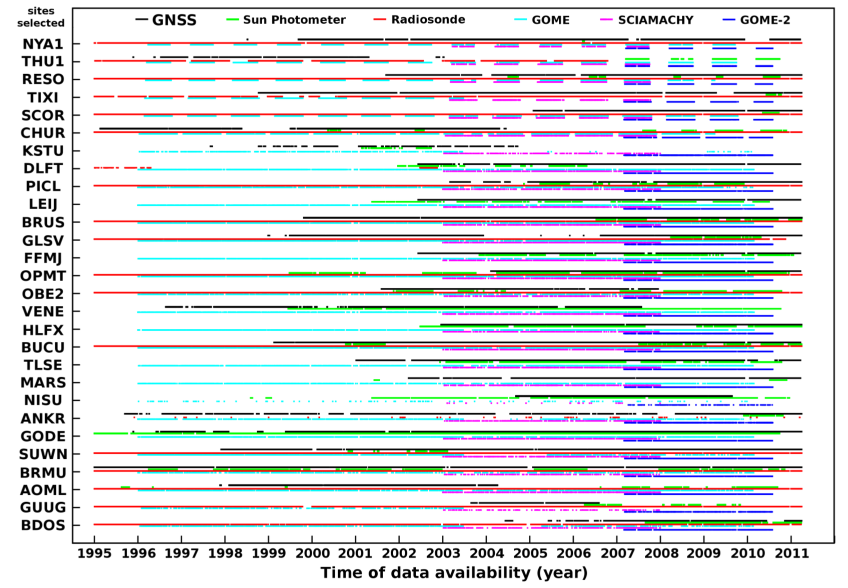


Fig. 2: IWV data availability over the last 15+ years for the different instruments at the selected sites.

Technique	Spatial Coverage	Temporal Resolution	Time Span	Tech. Costs	All Weather / All Direction	By Product of An Analysis
GNSS	± 350 IGS sites	every 5 minutes	1995-now	low	Yes / Yes	Yes
Radiosonde	± 1500 sites	on average twice/day	1950s-now	low to moderate	Yes / Vertical Profile	No
CIMEL Sun Photometers	± 300 sites	± 15 min, depending on weather conditions	1993-now	moderate	clear sky only / solar direction needed	No, but focus on aerosol properties retrieval
GOME(2)/SCIAMACHY	Global	maximum once/day	1996-now	very high	only if (almost) cloud free/nadir	No

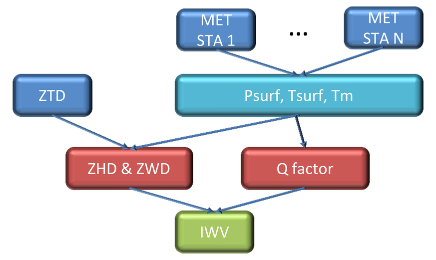
Table 1 : Pros & cons per technique.

2. Inter-Technique Comparisons

ZTD to IWV Conversion

To be compared to the other sources of water vapour observations, the GPS-based ZTD provided by the IGS reprocessed/final troposphere products needed to be converted into Integrated Water Vapour content (IWV). For that, we used the following synthetic algorithms:

1. Extracting the wet contribution (ZWD) from the ZTD by calculating the hydrostatic contribution (ZHD) based on a model and surface pressure records.
2. Computing the Q factor to convert the ZWD to IWV based on either surface meteorological records of the pressure and temperature (Psurf and Tsurf) and/or of the mean atmospheric temperature (Tm).



In this study, we preferred to work with purely observational data (Psurf and Tsurf), gathered at synoptic stations at a horizontal distance of maximum 50 km from the GNSS station.

Ref.: Bevis et al. [1992], Saastamoinen [1972], Askne and Nordius [1987] and Davis et al. [1985].

Instrument Colocation: focus on Brussels

As a first step, this study focused on Uccle, Brussels, Belgium (50°48'N, 4°21'E, 100m asl) presenting the following advantages:

- The different ground-based and in-situ instruments and the automatic weather station (time resolution: 10min) are really located at the same site, so that the horizontal and vertical separation of the different devices is not an issue.
- All techniques are available for this site.
- We dispose of the metadata of the different instruments, so that we are aware of any instrumental change that might give rise to an inhomogeneity of the instrument's data series.
- The availability of auxiliary weather data is a major advantage.

From Fig. 3, we note:

- The different instruments have different observation periods.
- We have 2 radiosonde types: Vaisala's RS80 and RS90/RS92 (=RS9x).
- The GPS IGS IWV is candidate for reference device because of data every 10min (since 1999*), only minor data gaps, homogeneous data (re)-processing by IGS.

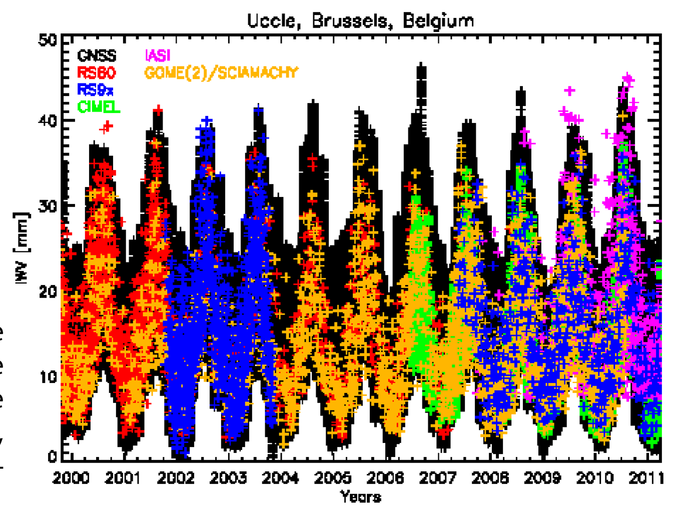


Fig. 3: Overview of all IWV data available at Uccle, Brussels.

* We dispose of weather data with 10 minutes of time resolution only since 1999.

Exploitation of the IWV Datasets @ Brussels

We constructed scatter plots of simultaneous (Δt = 10min for CIMEL, Δt = 30min for RS and GOME(2)/SCIAMACHY) IWV measurements between the different devices (using the GNSS as reference, see Fig. 4). These plots show that:

- The mean bias between the different techniques varies between -0.6 mm (GOME/SCIAMACHY) to 0.6 mm (RS9x).
- The best correlation and lowest dispersion of the data points are reached for the CIMEL vs. GNSS comparison.
- Vaisala's state-of-the-art radiosonde type (RS9x) compares better w.r.t. GNSS data than the preceding RS80 type.
- The slopes of regression lines w.r.t. GNSS are closer to 1 for other all-weather devices (RS) than for instruments demanding a partly clear sky (CIMEL, GOME(2)/SCIAMACHY).

We elaborated more on this last point for the CIMEL measurements. Therefore, we analysed the CIMEL-GNSS scatter plot properties for different types of cloudiness, observed at Uccle. We found that, the more clouds in the sky,

- The higher the average IWV measured by both CIMEL and GNSS.
- The lower the CIMEL-GNSS bias, i.e. the GNSS is measuring those higher IWV values more frequently than the CIMEL.
- The lower the slope coefficient of the linear regression line, which is almost entirely due to the high-range IWV measurements (where GNSS IWVs > CIMEL IWVs).

Clouds contribute directly to the GNSS IWV measurements (originally: different directions, towards satellites, which are then mapped to the zenith), but not in CIMEL IWV (originally: clear sky in solar slant then mapped to zenith by using the air mass).

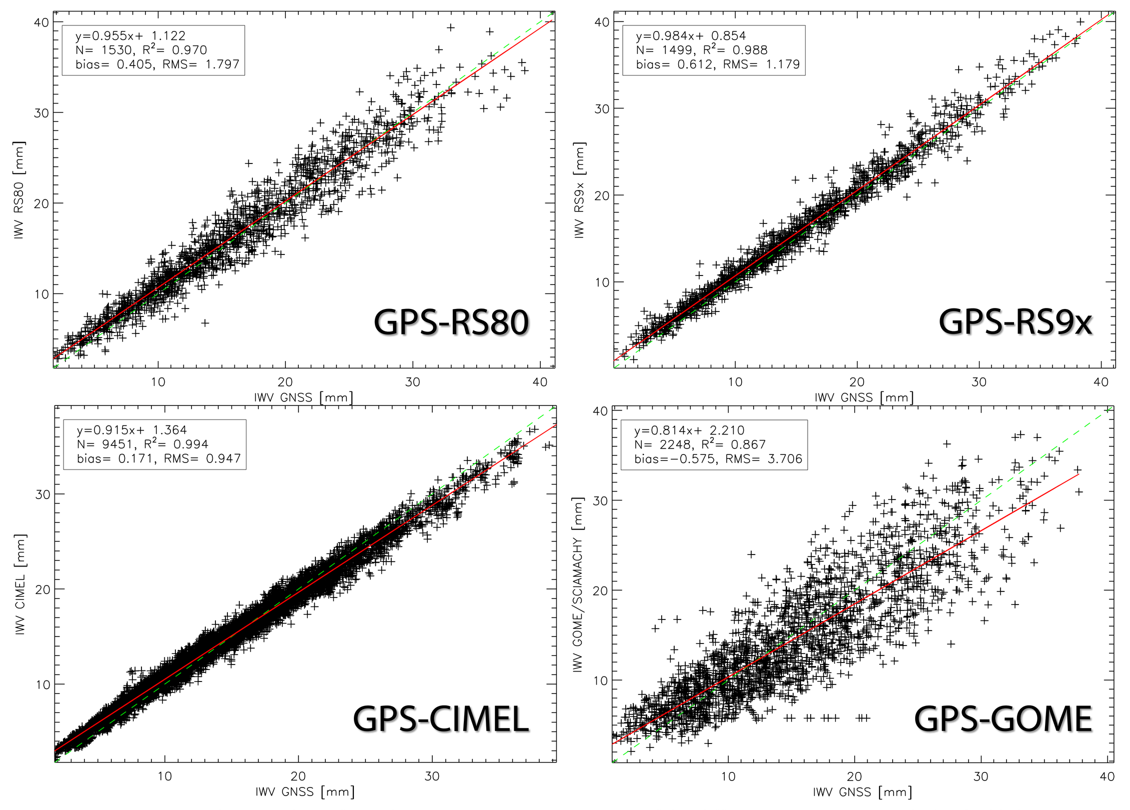


Fig. 4: Scatter plots of simultaneous IWV measurements of the different instruments with the GNSS device.

Solar-Slant IWV Comparisons @ Brussels

Then, we studied the influence of the different mapping function techniques (used for the GNSS and CIMEL IWV data conversion) on the properties of the GNSS-CIMEL scatter plots. Therefore, we calculated slant IWV (SIWV) in direction of the Sun as follow:

- For GNSS, IWV is converted in solar SIWV using the wet mapping function of *Niell* [1996]. Additional contribution of horizontal gradients in the azimuthal direction of the Sun are estimated with the mapping function of *Chen and Herring* [1997].
- For CIMEL, the solar slant SIWV values can be calculated by multiplying the IWV values with the optical air mass defined by *Kasten and Young* [1989].

Comparing the IWV and SIWV scatter plots (Figs. 4 and 5), we note that the regression slope is closer to unity for the SIWV measurements, hence there is possibly an impact of the different mapping function algorithms used by different devices on the resulting IWVs.

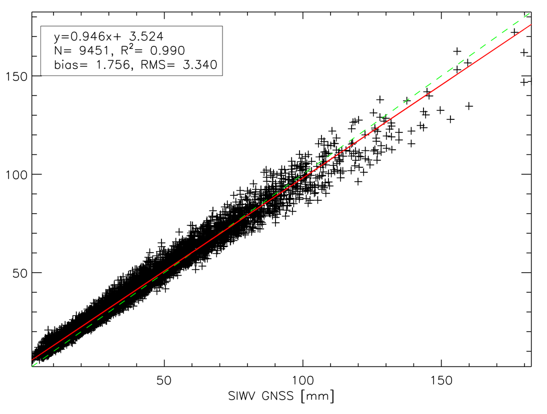


Fig. 5: Scatter plot of simultaneous CIMEL and GNSS solar slant IWV measurements at Uccle.

World-wide Exploitation of IWV Datasets

In a second step, we extended our study worldwide. We created scatter plots similar to Fig. 4 for the selected 28 sites for which we found instrumental co-location. Results are summarised in Figs. 6 and 7 and show that:

- The CIMEL instrument compares best with the GNSS technique for the IWV measurements (best correlation, lowest scatter).
- The regression slopes are for almost all instrument comparisons at all stations smaller than 1.
- At sites where different CIMELs can be compared with one IGS GNSS station (e.g. BRMU, NISU, TLSE, BUCU, VENE, OBE2, OPMT), significant differences exist between the regression slopes of the respective scatter plots → geographical dependency or remaining CIMEL calibration issues?
- There is neither latitudinal nor longitudinal dependency of the scatter plots properties.

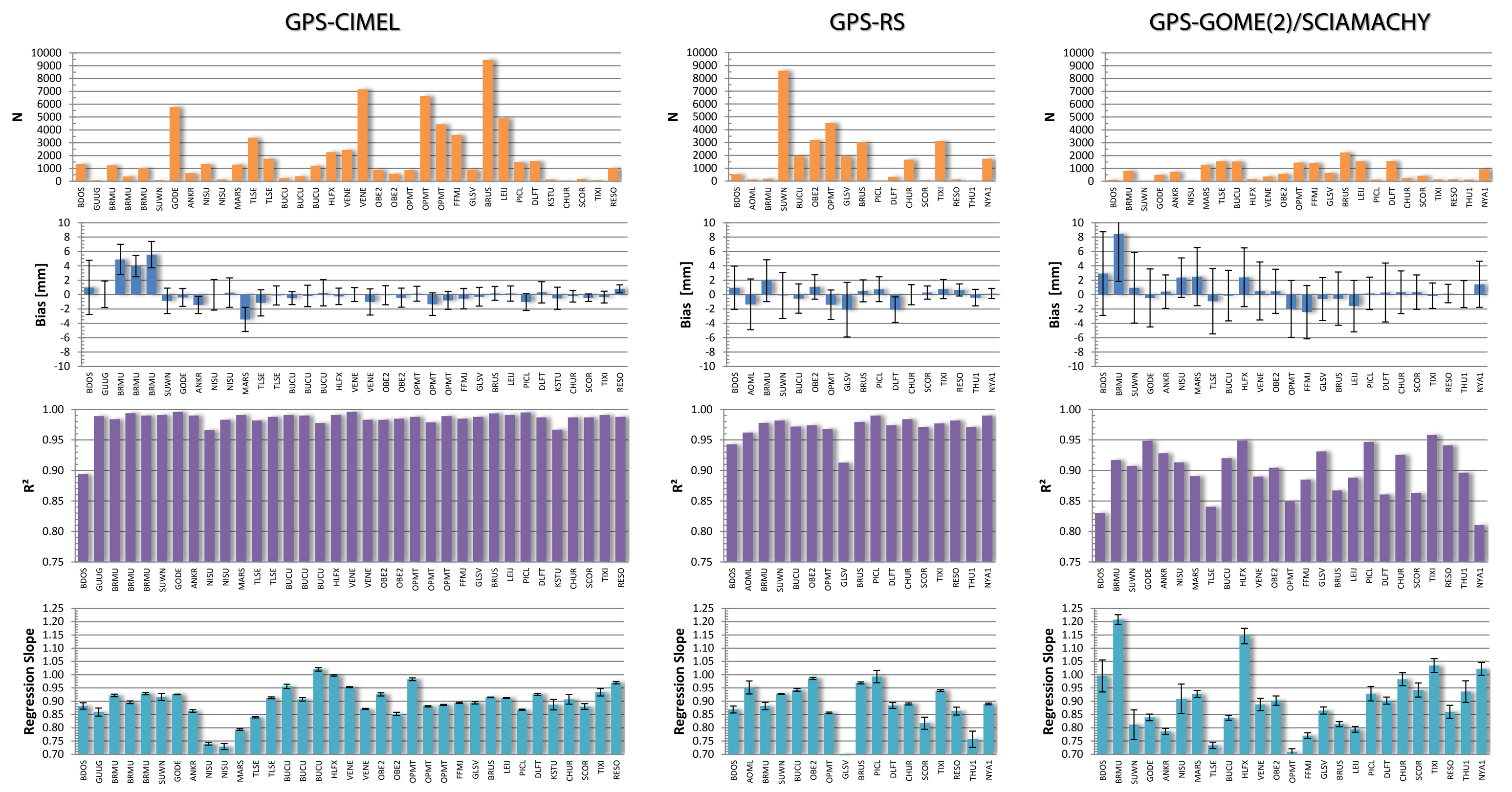


Fig. 6: Column bar plots of scatter plot properties (count N, bias, R^2 and regression slope) of the different instruments versus GNSS for the selected sites worldwide. Sites are ordered with increasing latitude. The error bars represent the RMS (bias) and the standard deviation (regression slope).

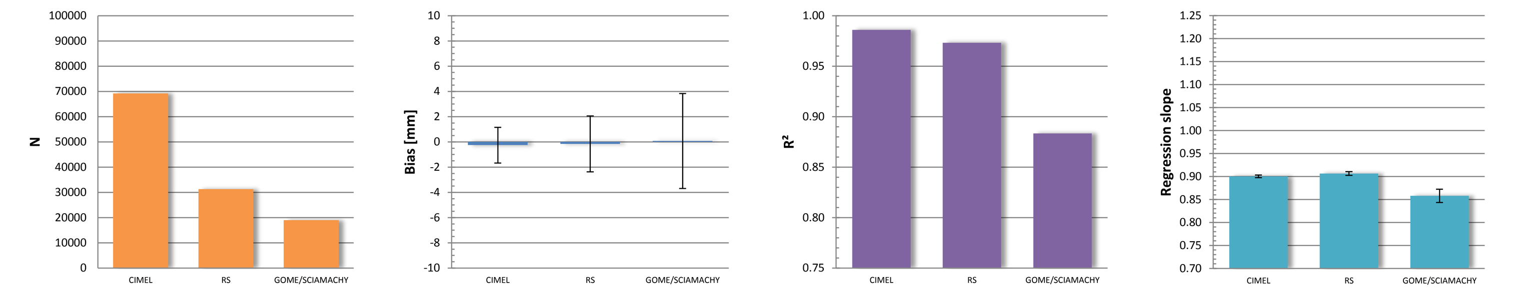


Fig. 7: Column bar plots of scatter plot properties (count N, bias, R^2 and regression slope) of the different instruments versus GNSS averaged over all stations included in the inter-technique comparison. Error bars: see Fig. 6.

3. Conclusions and Perspectives

- CIMEL sun photometers and GNSS are very valuable techniques to measure IWV and are the most promising to built up long time series for climate applications, as long as the data homogeneity can be guaranteed. For the CIMEL photometers belonging to the AERONET, a regular calibration of the instrument is required. IGS GNSS data were (re)processed homogeneously from 1994 on to mid-April 2011.
- For large IWV values, the GNSS instrument measures higher amounts of IWV than the CIMEL does. This can at least partly be explained by the observation bias of the CIMEL instrument: it requires a clear sky in the direction of the sun. But the larger the IWV values, the higher the probability to have clouds, which contribute directly to the GNSS observations, but not to the CIMEL IWV observations.
- Also the different instrumental approaches to map the measurements in the zenith direction might contribute to the different sensitivity of the CIMEL and GNSS devices to large and small amounts of IWV present in the atmosphere, as the comparison of simultaneous solar slant IWVs at Uccle showed.
- Radiosondes are launched in all weather conditions, but different radiosonde types compare differently for the IWV measurements to the co-located GNSS instrument (demonstrated by the Uccle case study), giving rise to a larger IWV scatter w.r.t. GNSS for RS stations having launched different types in time.
- The GOME(2)/SCIAMACHY IWV measurements are susceptible to a similar observation bias as the CIMEL (almost cloud free skies are needed), which is also reflected in the low mean value of the regression line slope. For these satellite data, the largest (but apparently random) geographical variability of the IWV measurements relative to the co-located GNSS observations is obtained.
- At this point of our research, there is no clear geographical pattern (e.g. related to the climate type) in the inter-technique comparisons at the selected sites worldwide.
- A possible future perspective is to analyse to which extent the different instrumental properties (and hence observation biases) influence the trends in the IWV time series.
- The current research will be submitted to the ACP special issue "Water Vapour in the Climate System (WAVACS) COST action: observations, processes, and modelling".

References and Acknowledgements

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