

Report on the project

Probing extreme weather events in a warming climate with GNSS and atmospheric reanalysis in the Azores Islands

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Abstract

The extent and dynamics of the semi-permanent North Atlantic high-pressure system known as the “Azores High” influence the weather and climatic patterns of the Azores Islands, affecting vast areas of western Europe, northern Africa, and the Mediterranean Basin. Climate change is increasing the intensity and frequency of extreme weather events in the Azores and globally. We have used atmospheric water vapor data from GNSS and reanalysis products from an atmospheric general circulation model (MERRA-2) to investigate the dynamics of weather fronts in the Azores, and to explore how extreme weather events are affected by climate change. We have utilized new GNSS approaches to investigate small-scale atmospheric structures with high temporal resolution, which have been cross-compared with a MERRA2-based atmospheric reanalysis approach developed at MIT. Atmospheric studies are important for understanding climatic changes in extreme weather and for mitigating weather-related hazards such as torrential downpours and landslides for the Azoreans.

Plain language summary:

The extent and dynamics of the North Atlantic semi-persistent high-pressure system known as the “Azores High” influence the weather and climatic patterns in the Azores Islands, western Europe, and beyond. The frequency and intensity of extreme weather events in the Azores, and globally, are increasing due to climate change. We have used atmospheric water vapor data from GNSS and reanalysis products from an atmospheric general circulation model to investigate how extreme weather events in the Azores are affected by climate change. This understanding is important for mitigating the impact of weather hazards for the Azoreans.

Accomplishments:

This project helped us to explore how GNSS techniques can be utilized to probe small-scale atmospheric structure. As a part of the project, we presented 5 posters in several international conferences [Brock et al., 2023; Mondal et al., 2024a, b; Mateus et al., 2024; Ramrajvel, 2025], trained UROP students Lucy Brock, Beshr Islam, and Nathra Ramrajvel, and REU student Noah Harley. We also submitted one manuscript for publication in Geophysical Research Letters, entitled “*Major melting event on the Ross Ice Shelf, Antarctica, connected with enhanced atmospheric turbulence.*”

Interactions with the Portuguese collaborator(s):

Pls Mondal and Elosegui (MIT), Paine (Harvard & Smithsonian), and Mateus (University of Lisbon) have been actively collaborating since the submission of this project. As a part of the ongoing collaboration, we participated in the project (as collaborators), “GNSS Atmospheric TOMography: probing storms in a warming climate (GATO),” which was awarded to our Portugal colleagues by the Portugal Science Ministry, the Portuguese counterpart of the MIT Portugal Program. The collaboration is balanced, solid, and prolific, and has great promise to flourish into a sound collaborative research program should further funding be made available.

References:

Brock, L., Mondal, D., Elosegui P., Paine, S., Mateus, P., and Mendes, V.B., 2023 *Probing extreme weather events in a warming climate with GNSS and atmospheric reanalysis in the Azores Islands*. MIT Portugal 2023 Annual Conference.

Ramrajvel, N., D. Mondal, P. Elosegui, S. Paine, P. Mateus, V. Mendes. 2025. *Decoding the signal of extreme weather events in the Azores archipelago using GNSS and atmospheric reanalysis products*, EGU25-13415, <https://doi.org/10.5194/egusphere-egu25-13415>.

Mondal, D., Elosegui P., Brock, L., Paine, S., Mateus, P., and Mendes, V.B., 2024a. *Probing the Dynamics of Extreme Weather Events in the Azores, Portugal*. No. EGU24-5929. Copernicus Meetings.

Mondal, D.R., Elosegui, P. and Paine, S., 2024b. *Atmospheric turbulence on the Ross Ice Shelf, Antarctica, during the January 2016 melting event*. In *AGU Fall Meeting Abstracts* (Vol. 2024, No. 503, pp. C13A-0503)

Mondal, D.R., Elosegui, P., Ramrajvel, N., and Paine, S., 2025. *Major melting event on the Ross Ice Shelf, Antarctica, connected with enhanced atmospheric turbulence*. nGeophysics Research Letters (submitted)

Mateus, P., Mendes, V.B., Miranda, P.M., Mondal, D.R. and Elosegui, P., 2024. *Monitoring Atmospheric Water Vapor Cost-Effectively Using GNSS Tomographic Methods*. In *AGU Fall Meeting Abstracts* (Vol. 2024, No. 336, pp. G33A-336).

Appendix:

1. Poster presented to the MIT Portugal conferences in 2023.

Probing extreme weather events in a warming climate with GNSS and atmospheric reanalysis in the Azores Islands

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MIT Portugal 2023 Annual Conference

Abstract

The frequency and intensity of extreme weather events in the Azores islands have been increasing due to climate change. Understanding these changes is important for mitigating the impact of weather hazards. We use atmospheric water vapor data from the Global Navigation Satellite System (GNSS) and reanalysis products from an atmospheric general circulation model (MERRA) to investigate the dynamics of weather fronts in the Azores. Our main objective is a comprehensive comparison of GNSS and MERRA-based atmospheric reanalysis data to probe small-scale atmospheric structures and their embedding larger-scale environment with high-temporal resolution. Through statistical analysis, we aim to study the similarities and discrepancies between the GNSS-based approach and the MERRA reanalysis in capturing atmospheric water vapor patterns. We will present our exploratory approach using a limited dataset focused on selected extreme precipitation events recorded in the Azores Islands.

Intro/Background

- The Global Navigation Satellite System (GNSS) is a powerful meteorological sensor that can provide continuous measurements of precipitable water vapor with about 1 mm precision.
- While a single GNSS station can measure the total water vapor along the zenith direction every few minutes, a GNSS network [Fig. 1] forms inter-site combinations of water vapor estimates that provide deeper insight into the structure and dynamics of the atmosphere above¹.
- The Modern-Era Retrospective Analysis for Research and Applications-2 (MERRA-2) version of the Goddard Earth Observing System-5 (GEOS-5) atmospheric general circulation model is the first long-term global reanalysis to assimilate space-based observations of aerosols and represent their interactions with other physical processes in the climate system².

Figure 1: GNSS networks sense weather (such as the movement of frontal systems) via the induced delay in GNSS signals due to the neutral atmosphere.

Methods

- This preliminary study focuses on comparing atmospheric water vapor data from GNSS and MERRA-2 reanalysis products to gain insights into the dynamics of extreme weather events in the Azores Islands.
- The dataset spans the years 2012 to 2017, incorporating a temporal resolution of up to once every 3 hours for MERRA-2 and once every 300 seconds for GNSS.
- Four GNSS sites—FLRS, FRNS, POEL, and TERC—were selected for analysis, with direct comparisons against corresponding MERRA-2 data at each location [Fig. 2].
- The four sites were chosen not only to get a spread from east to west, but also in order to have direct comparisons for vertical profiling. The POEL and FRNS stations are located on the same island, at different elevations, providing a proxy for tomography that could be useful for future projects.

Figure 2: GNSS Stations. GNSS networks operating continuously in the Azores islands and (inset) small-scale, high-density GNSS network proposed to be deployed in Terceira. Here, we focus on a limited dataset consisting of the FLRS, FRNS, POEL, and TERC stations.

Figure 3: PWV Timeseries. PWV comparison between (red) GNSS and (blue) MERRA-2 atmospheric model reanalysis for the POEL GNSS station on the Azores Islands, showing close agreement in capturing the seasonal cycles. Due to gaps in the GNSS data, only the matched timestamps for both sources are shown. For future work, we can tailor this comparison study to specific extreme events, such as Hurricane Ophelia (inset).

Figure 4: Autocorrelations. PWV autocorrelation plots showing differences between MERRA-2 observations and GNSS data. This demonstrates one significant way in which the two models can complement each other to prepare more accurate forecasts.

Figure 5: Seasonal Variation. PWV seasonal variation comparison between GNSS and MERRA-2 atmospheric model reanalysis for the FLRS, FRNS, POEL, and TERC GNSS stations on the Azores Islands. Comparing these two probes statistically reveals biases in individual metrics that are important to note, as we may use one method to build up the other for enhanced probing of extreme weather events.

Figure 6: Cumulative PWV Distribution. Net PWV probability distributions, showing close agreement between the GNSS and MERRA-2 values. Using this combination of atmospheric observables, we can create more physically meaningful studies of atmospheric structure over small scale-networks, such as the future GNSS tomography study at Terceira Island [Fig. 2 inset], which will identify and focus on atmospheric precipitation events of significance in the Azores.

Conclusions

In this preliminary study, we performed a comparison of GNSS and MERRA-2 data, primarily focusing on atmospheric water vapor patterns, due to their relevance to extreme weather events in the Azores for a future study. The strong correlations observed in various PWV metrics underscore the potential utility of both data sources for characterizing these events. These results lay the foundation for a more comprehensive investigation that will delve deeper into the integration of GNSS and MERRA-2 data, and which will have important implications for improved weather forecasting for Azoreans, and for enhanced probing of extreme weather events in Portugal and Western Europe.

References

- Cresswell-Clay, N., et al., 2022. Twentieth-century Azores High expansion unprecedented in the past 1200 years. *Nature Geoscience*, 15(7), pp.548-553.
- Elosegui, P., Davis, J.L., Gradinarsky, L.P., Elgered, et al., 1999. Sensing atmospheric structure using small-scale space geodetic networks. *Geophysical research letters*, 26(16), pp.2445-2448.
- Celliers, R., et al., 2017. "The Modern-Era Retrospective Analysis for Research and Applications, Version 2 (MERRA-2)." *Journal Climate*. <https://doi.org/10.1175/JCLI-D-16-0758.1>.

Co-funded by:

under the Seed Project: Probing extreme weather events in a warming climate with GNSS and atmospheric reanalysis in the Azores Islands | Climate Science & Climate Change

2. Poster presented to the EGU (European Geophysical Union) meeting in 2024

Probing the Dynamics of Extreme Weather Events in the Azores, Portugal

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Motivations/Objectives

- The frequency and intensity of extreme weather events in the Azores, Portugal, (and globally) are on the rise due to climate change, necessitating a deeper understanding of the dynamics leading to these events for effective mitigation.
- Global Navigation Satellite System (GNSS) data and atmospheric general circulation models, such as MERRA-2, are two independent yet complementary techniques to investigate the dynamics of weather frontal systems.
- Statistical analysis of combined GNSS and MERRA-2 data, focusing on small-scale atmospheric structures at high-temporal resolution, can uniquely probe into atmospheric water vapor patterns.

Background

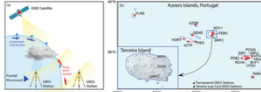


Figure 1: (a) GNSS signal delays due to the neutral atmosphere which can be used to sense weather (such as the movement of frontal systems). (b) Continuously operating GNSS networks in the Azores archipelago and (inset) small-scale, high-density GNSS network (under deployment) in Terceira Island.

- GNSS, as a meteorology sensor, can measure precipitable water vapor (PWV) with mm-level precision.
- A single GNSS site provides point-like PWV measurements along the zenith direction every few minutes; a GNSS network samples the time-varying PWV distribution over a region thus probing into atmospheric structure and dynamics.
- MERRA-2 provides multidecadal reanalysis of aerosol and meteorological observations within a global data assimilation system for a broad range of variables, including PWV.
- The combination of GNSS and MERRA-2 facilitates comprehensive analysis of atmospheric dynamics, offering valuable data for understanding and predicting weather patterns and climate change impacts.

Data & Methods

- For this study, we used GNSS tropospheric products from the Nevada Geodetic Laboratory (INGL) and MERRA-2 gridded products from the NASA website, both for years 2012–2017.
- We utilized the data from the continuously operating GNSS network in the Azores to explore tropospheric delay variability, but only four sites (i.e., FLRS, FRNS, PDEL, and TERC; see Fig. 1b) for comparisons with MERRA-2.

PWV time series

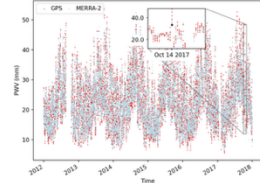


Figure 2: Example of temporal variation of PWV from (red) GNSS and (blue) MERRA-2 for the GNSS site at PDEL (Fig. 1b) with (inset) a PWV spike due to hurricane Ophelia.

- PWV estimates from GNSS and MERRA-2 during 2012–2017 are in close (overall) agreement, both capturing the seasonal (i.e., summer–winter) PWV cycles.
- The sharp PWV rise on 2017 October 14 demonstrates how both techniques are sensitive to extreme events such as Ophelia (Fig. 2 inset), a major hurricane that battered the Azores with high winds and heavy rainfall.

PWV time-series auto-correlations

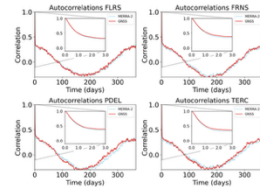


Figure 3: Examples of auto-correlations of PWV time series from GNSS and MERRA-2 at four GNSS locations (see Fig. 1b).

- The agreement between PWV auto-correlations from GNSS and MERRA-2 time series at the four GNSS locations highlights the complementarity of both techniques for atmospheric probing of extreme events.

Seasonal PWV variations

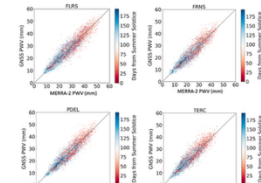


Figure 4: Scatter plot of PWV as measured by GNSS and MERRA-2 at the same four GNSS locations as in Fig. 3 and for the full 2012–2017 period, where color groups PWV estimates for the same year-days over all years. The thin line traces the values where GNSS and MERRA-2 PWV estimates are equal.

- Seasonal PWV variation as measured by GNSS and MERRA-2, demonstrating (implied) correlation.
- There is a hint that GNSS estimates might be slightly higher than MERRA-2 for high PWV values, but further analysis is warranted.

Cumulative PWV distribution

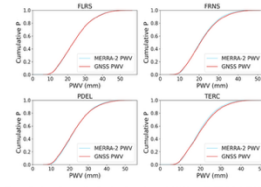


Figure 5: Cumulative distribution functions of GNSS and MERRA-2 PWV estimates at the same four GNSS locations as in Fig. 3.

- Cumulative distribution functions (CDF) of GNSS and MERRA-2 demonstrate the sampled PWV probabilities are mutually consistent.
- Using this combination of atmospheric observables, one can study the atmospheric structure over small networks, such as in Terceira Island (Fig. 2 inset).

Spatial variation of tropospheric delay

- Tropospheric delay variations between two locations (e.g., site 1 at r and site 2 at $r + b$) can be calculated using the so-called structure-function D

$$D(b) = \overline{\delta[(r + b) - r]^2}$$

where $b = b$ is the inter-site distance or baseline length, δ a stochastic variable there “zenith total delay”, and $\overline{\delta[\cdot]}$, the expected value (Fig. 6).

- The structure-function can be modeled using a power law
$$D(b) = \sigma_a^2 + C^2 \left(\frac{b}{B}\right)^\alpha$$

where σ_a^2 is a non-atmospheric variance, C^2 a structure constant, B a scale length (in km), and α the power-law exponent (e.g., 2/3 according to Kolmogorov turbulence theory).

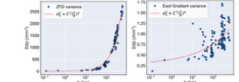


Figure 6: Variograms of (left) zenith total delay and (right) East gradient delay parameter between GNSS sites in the Azores for the years 2012–2017.

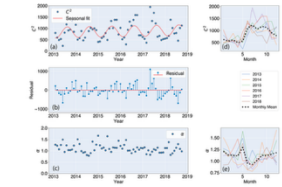


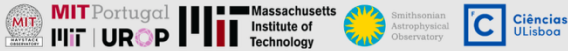
Figure 7: Monthly estimates of (left) parameters C^2 – and the residual about the seasonal signal – and α , and (right) their monthly mean of C^2 .

- Seasonal variation of C^2 indicates higher atmospheric turbulence in the summer.

Summary and future work

- Comparison of GNSS and MERRA-2 PWV shows strong correlations indicating potential for improved extreme weather event characterization.
- PWV as well as other tropospheric parameter estimates from the GNSS network spanning the Azores archipelago can help better understand atmospheric dynamics over this region.
- The results lay the groundwork for further integration of GNSS and MERRA-2 products, to investigate the impact of climate change in the Azores and thus advance effective mitigation.

Affiliations



Meeting

European Geosciences Union 2024
Poster number - 5929
04/17/2024 8:00-10:00 AM EDT
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Acknowledgment

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3. Poster presented to the EGU (European Geophysical Union) meeting in 2025

Decoding the signal of extreme weather events in the Azores archipelago using GNSS and atmospheric reanalysis products

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Background and Motivation

- Extreme weather events are becoming more frequent and intense in the Azores and globally due to climate change, highlighting the need to better understand their causes for effective mitigation.
- GNSS data and atmospheric models like MERRA-2 offer complementary ways to study weather fronts [Fig. 1].

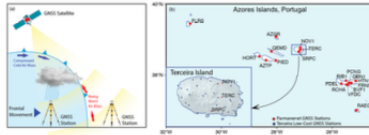


Figure 1: (a) GNSS signal delays due to the neutral atmosphere which can be used to sense weather (such as the movement of frontal systems). (b) Continuously operating GNSS networks in the Azores archipelago and (inset) small-scale, high-density GNSS network (under deployment) in Terceira island.

- A single GNSS site measures point precipitable water vapor (PWV) along the zenith every few minutes, while a GNSS network captures regional PWV variations, revealing atmospheric structure and dynamics.
- MERRA-2 offers multidecadal reanalysis of aerosol and meteorological data, including PWV, through a global data assimilation system.
- Combining PWV from a network of GNSS stations and MERRA-2 enables high-resolution analysis of small-scale water vapor patterns in the atmosphere.

Data & Methods

- For this study, we used GNSS tropospheric products from the Nevada Geodetic Laboratory (NGL) (from 2012–2019), and MERRA-2 gridded products from the NASA website, for the year of 2017.
- We utilized the data from the continuously operating GNSS network in the Azores to explore tropospheric delay variability, but only 4 sites (i.e., VFDC, RAEG, AZGR, QEMD; see Fig. 1b) for comparisons with MERRA-2.
- We calculate the PWV using “am” (atmospheric model) version 14.0 [Paine 2024].
- We calculate wet delay structure function and estimated structure constant C^2 , to test whether the turbulence during extreme event can be detectable using a network of GNSS.

PWV time-series

- PWV estimates from MERRA-2 using “am”. The red vertical line on 2017 October 14 shows the timing of hurricane Ophelia [Fig. 2 inset] that battered the Azores with high winds and heavy rainfall.

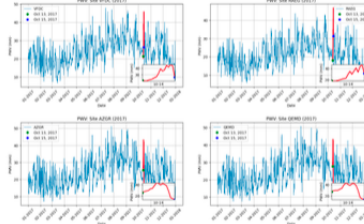


Figure 2: PWV time-series from (blue) MERRA-2 for four GNSS sites over 2017 with (inset) a (red) PWV spike during hurricane Ophelia.

PWV time-series MERRA-2 vs GNSS

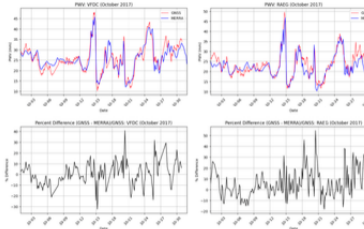


Figure 3: Comparison of GNSS and MERRA-2 via PWV time series and percentage difference from at GNSS sites VFDC and RAEG over October 2017.

- The GNSS and MERRA-2 estimates show good agreement, as further visualized by the percentage difference staying within 20 percent for the majority of the data points.
- Notably, the percentage difference is positive most of the time, indicating the GNSS measurements are on average slightly higher.

Spatial variation of tropospheric delay

- The zenith wet delay (zwd) variations between two sites (e.g., site 1 at r and 2 at $r + b$) is calculated using the so-called structure-function D

$$D(b) = E[(l(r+b) - l(b))^2] = \sigma_0^2 + C^2 \left(\frac{b}{B}\right)^\alpha$$

where $b = b$ is the baseline length or distance between two stations, l a stochastic variable (here “zenith wet delay”), and $E[\cdot]$ the expected value. The structure-function can be modeled using a power law, where σ_0^2 is a non-atmospheric variance, C^2 a structure constant, B a scale length (in km), and α the power-law exponent (e.g., 2/3 according to Kolmogorov turbulence theory).

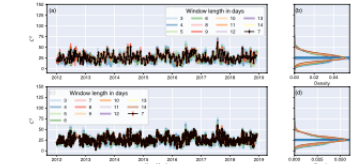


Figure 4: (a) Multi-day C^2 estimates using non-overlapping, fixed-length time windows from 3 to 14 days, with error bars on the (red circles) weekly estimates, and (c) daily C^2 estimates using overlapping (1-day step), variable-length time windows from 3 to 14 days. (b) and (d) are the respective C^2 estimate histograms, both showing a median C^2 of about 25.

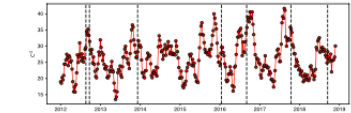


Figure 5: 30-day running mean of C^2 estimates. Vertical bars indicate the timing of the hurricanes in Azores archipelago.

Summary and future work

- Preliminary results show strong correspondence between GNSS and MERRA-2 PWV, supporting better extreme weather analysis.
- GNSS-derived PWV-structure function can be used to study atmospheric dynamics (further investigation needed).
- Results support combining GNSS and MERRA-2 to study climate change impacts in the Azores.

Affiliations



Meeting

European Geosciences Union 2025
05/01/2024 7.00-8.45 AM EDT
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Acknowledgment

Portuguese Foundation for International Cooperation in Science, Technology, and Higher Education (Govt. of Portugal), and MIT Portugal Program

4. Poster presented to the AGU (American Geophysical Union) meeting in 2024



Atmospheric turbulence on the Ross Ice Shelf, West Antarctica, during the January 2016 melting event

Dhiman Mondal¹, Pedro Elosegui^{1,2}, Nathra Ramrajvel¹, and Scott Paine³

¹MIT Haystack Observatory, Westford, MA, USA; ²Institute of Marine Sciences, ICM-CSIC, Barcelona, Spain; ³Center for Astrophysics | Harvard & Smithsonian, Cambridge, MA, USA



• Motivation and objectives

- The Ross Ice Shelf (RIS), West Antarctica, experienced extensive surface melting in January 2016, a significant event since 1980 [Fig. 1].
- The event was caused by basal and surface melting, the latter due to warm and humid air transported from the Southern Ocean.
- A few studies have indicated the existence of turbulent mixing of the atmosphere (e.g., Hu et al., 2019).
- Here, we explore the use of an existing GNSS network on the RIS to study atmospheric turbulence during the melting event.

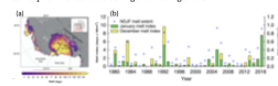


Figure 1: (a) Total number of melt days in West Antarctica in January 2016 from passive microwave satellite data. (b) Summer melt index and extent in the Ross Sea. (Modified after Nicholas et al., 2017.)

• Atmospheric turbulence using GNSS

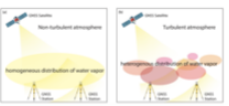


Figure 3: GNSS stations can probe the spatio-temporal distribution of water vapor in the atmosphere because it induces a measurable delay. Water vapor distribution is spatially (a) homogeneous in a non-turbulent atmosphere and (b) heterogeneous when the atmosphere is turbulent.

- GNSS, as a meteorology sensor, can measure precipitable water vapor (PWV) with mm-level precision [Fig. 3].
- A GNSS site provides point-like measurements of water-vapor delay (or wet delay) along the zenith direction every few minutes.
- A GNSS network samples the time-varying water-vapor distribution over a region thus probing into atmospheric structure and dynamics [Nilsson et al., 2009].
- The zenith wet delay I^w variations between two locations (e.g., site 1 at $\mathbf{r}$ and site 2 at $\mathbf{r} + \mathbf{b}$) can be calculated using a structure function D as
$$D(b) = E \left[\left(I^w(\mathbf{b}) - I^w(\mathbf{r} + \mathbf{b}) - E[I^w(\mathbf{b}) - I^w(\mathbf{r} + \mathbf{b})] \right)^2 \right] \quad (1)$$
where $\mathbf{b} = |\mathbf{b}|$ is the baseline length (or distance between sites), $E[\cdot]$ a stochastic variable, and $E[\cdot]$ the expected-value operator.

• Atmospheric turbulence in the RIS

- We modeled the zenith wet delay variability between two GNSS stations as
$$D(b) = \sigma_\epsilon^2 + C^2 \left(\frac{b}{B} \right)^\alpha \quad (2)$$
where σ_ϵ^2 is a non-atmospheric variance, C^2 a structure constant, B a scale length (in this case 200 km, the mean baseline length), and α the power-law exponent (e.g., 2/3 after Kolmogorov turbulence theory).
- We estimated the unknown parameters σ_ϵ^2 , C^2 , and α , and their uncertainties, for the entire period using a non-linear least-squares estimator and Bayesian inference (Fig. 5). (We used the PyMC/Python library to estimate C^2 , σ_ϵ^2 , and α , starting from normally distributed priors as our initial guess as $C^2 \sim N(0, 10)$, $\sigma_\epsilon^2 \sim N(0, 10)$, and $\alpha \sim N(2/3, 10)$.)
- In what follows, we restrict the discussion to the non-linear least-squares results because both methods produce consistent results (Table 1, Fig. 5) and Bayesian inference is computationally far more taxing.

Parameter	Estimate	Uncertainty	Bayesian estimate	Uncertainty
C^2	10.45	0.47	11.41	2.64
σ_ϵ^2	15.42	0.97	16.50	2.09
α	1.28	0.12	1.31	0.10

• Atmospheric turbulence during melting event

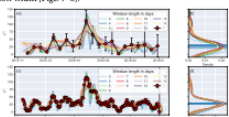


Figure 7: (a) Multi-day C^2 estimates using non-overlapping, fixed-length time windows from 3 to 14 days, with error bars on the red circles weekly estimates, and (c) daily C^2 estimates using overlapping (1-day step), variable-length time windows from 3 to 14 days. (b) and (d) are the respective C^2 estimate histograms, both showing a median C^2 of about 25. In mid-January 2016, C^2 estimates exceed the median by about 4.

- We estimated time-varying turbulence model parameters (i.e., σ_ϵ^2 , C^2 , and α) around the melting event using a fixed-length, variable-step, sliding window batch non-linear least-squares, with window widths ranging between 3 and 14 days and step size between 1 day and the window width [Figs. 7-8].
- C^2 is 4 times higher during the melting event in mid-January as evident from both sliding and rolling-based estimates (Fig. 7).
- Short (3-4 days) time-window lengths may possibly be resolving the two melting phases (shown in Fig. 2).

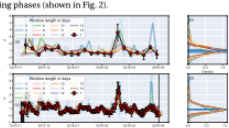


Figure 8: Same as Fig. 8 but here for α , whose median value is about 1.

• Baseline length and height distribution

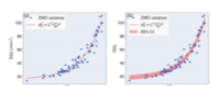


Figure 5: (Blue dots) observed (Fig. 1) zenith-wet-delay variance and (red line) modeled (Fig. 2) using (a) non-linear least-squares and (b) Bayesian inference.

- The 13-station GNSS network results in 78 zenith-wet-delay pair-wise combinations that are evenly distributed.
- Baseline lengths range between 20 and 440 km [Fig. 6a].
- Height separations between most (85%) station pairs are less than 35 m [Fig. 6b]. For this reason, adding model complexity to Eq. 2 by including a water-vapor-isotropy term seems unwarranted to first order.

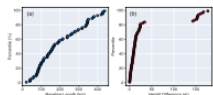


Figure 6: (a) Length and (b) height separation of station pairs that result from the GNSS network.

• Summary

- Mid-January 2016 was characterized by noticeably higher C^2 values in the RIS than the times surrounding, indicating higher atmospheric turbulence and mixing.
- The times of enhanced atmospheric turbulence in the RIS show excellent concurrence with the extensive melting event observed by other authors and means.
- This study opens up the possibility that GNSS could be used to augment existing atmospheric networks for enhanced cryosphere studies.

• Antarctica January 2016 melting event

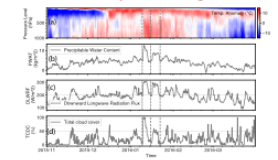


Figure 2: (a) Temperature anomalies in the troposphere, (b) precipitable water content, (c) downward longwave radiation flux, and (d) total cloud cover from November 2015 to April 2016. Three vertical lines on panels (a)-(d) mark the two main phases of the January 2016 melting event.

- The RIS experienced three weeks of anomalously warm atmospheric temperatures in Summer 2015-2016 (Fig. 2), causing extensive melting.
- The melting was linked to enhanced downward longwave (LW) radiative fluxes at the surface, influenced by water vapor and clouds as seen from NCEP/NCAR data [Fig. 2].
- Poleward wind anomalies and positive LW flux anomalies, driven by warm air and moisture advection from lower latitudes, caused rapid warming and extensive ice mass loss in West Antarctica [Hu et al., 2019].
- A few studies have also suggested that El Niño played a vital role in the melting (e.g., Nicholas et al., 2017).

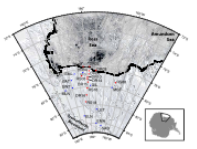


Figure 4: Geographical location of the (red circles) GNSS and (blue squares) weather station networks operational on the RIS during the January 2016 melting event. The underlying image is the corrected cloud reflectance from the Terra satellite on 2016 January 15, at the onset of the melting event. The inset shows the Antarctic location of the RIS.

Meeting



American Geophysical Union 2024
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12/09/2024 13:40 - 17:30 EST
Contact: dmondal@mit.edu

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