Report on the project

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

Principal Investigator:
Dhiman Mondal, Research Scientist, MIT Haystack Observatory, USA

Co-investigators:
Pedro Elosegui, Research Scientist, MIT Haystack Observatory, USA
Lucy Brock, Undergraduate Student, Earth, Atmospheric and Planetary Sciences, MIT, USA
Nathra Ramrajvel, Undergraduate Student, Department of Math and Computer Science, MIT, USA
Scott Paine, Research Scientist, Center for Astrophysics | Harvard & Smithsonian, USA
Pedro Mateus, Professor, Faculty of Science, University of Lisbon, Portugal
Virgilio Mendes, Professor, Faculty of Science, University of Lisbon, Portugal

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):
PIs 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.

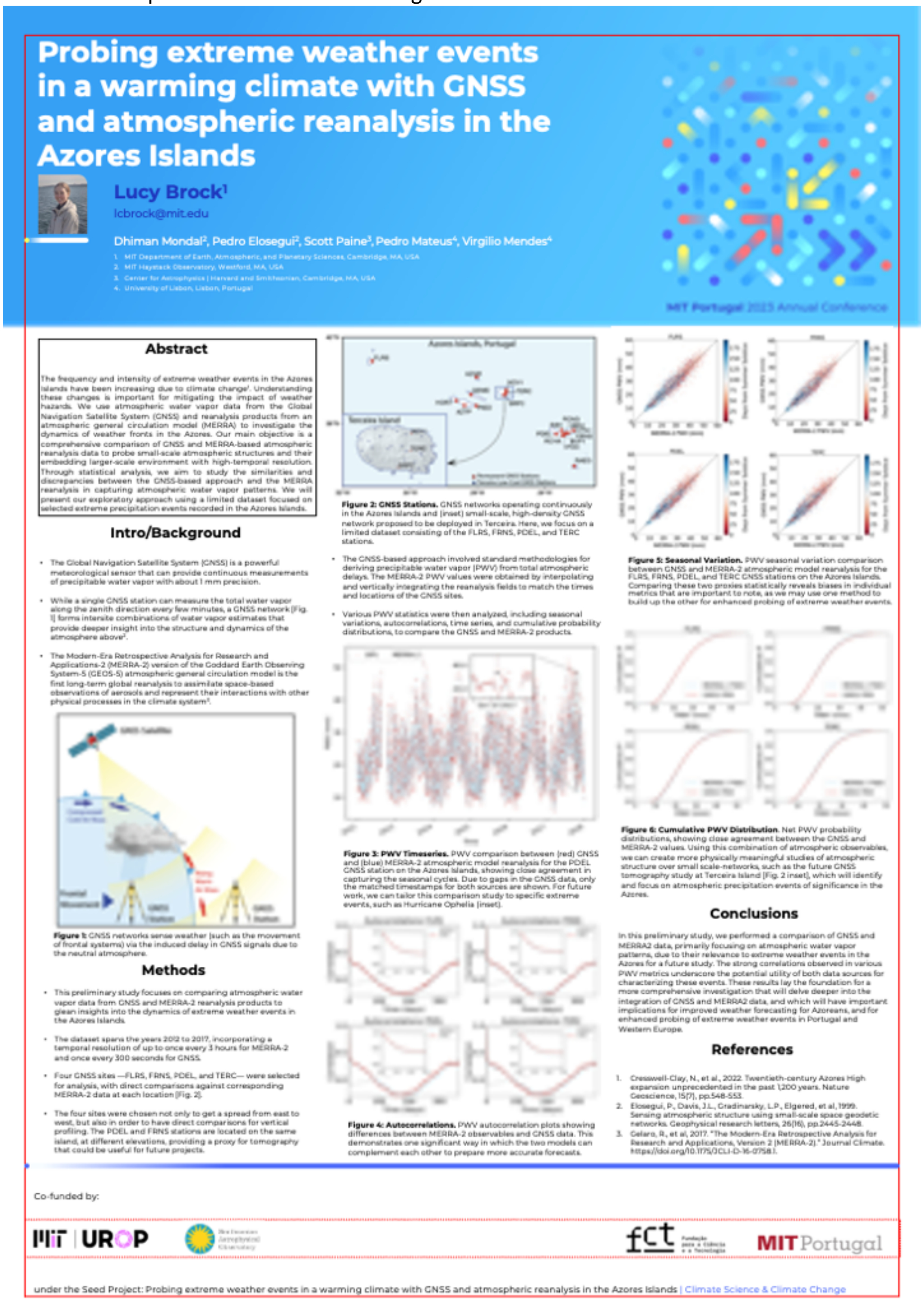
Mondal, D.R., Elosegui, P. and Paine, S., 2024b. *Atmospheric turbulence on the Ross Ice Shelf, Antarctica, during the January 2016 melting event*. In *AGU Fall Meeting Abstracts* (Vol. 2024, No. 503, pp. C13A-0503)

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)

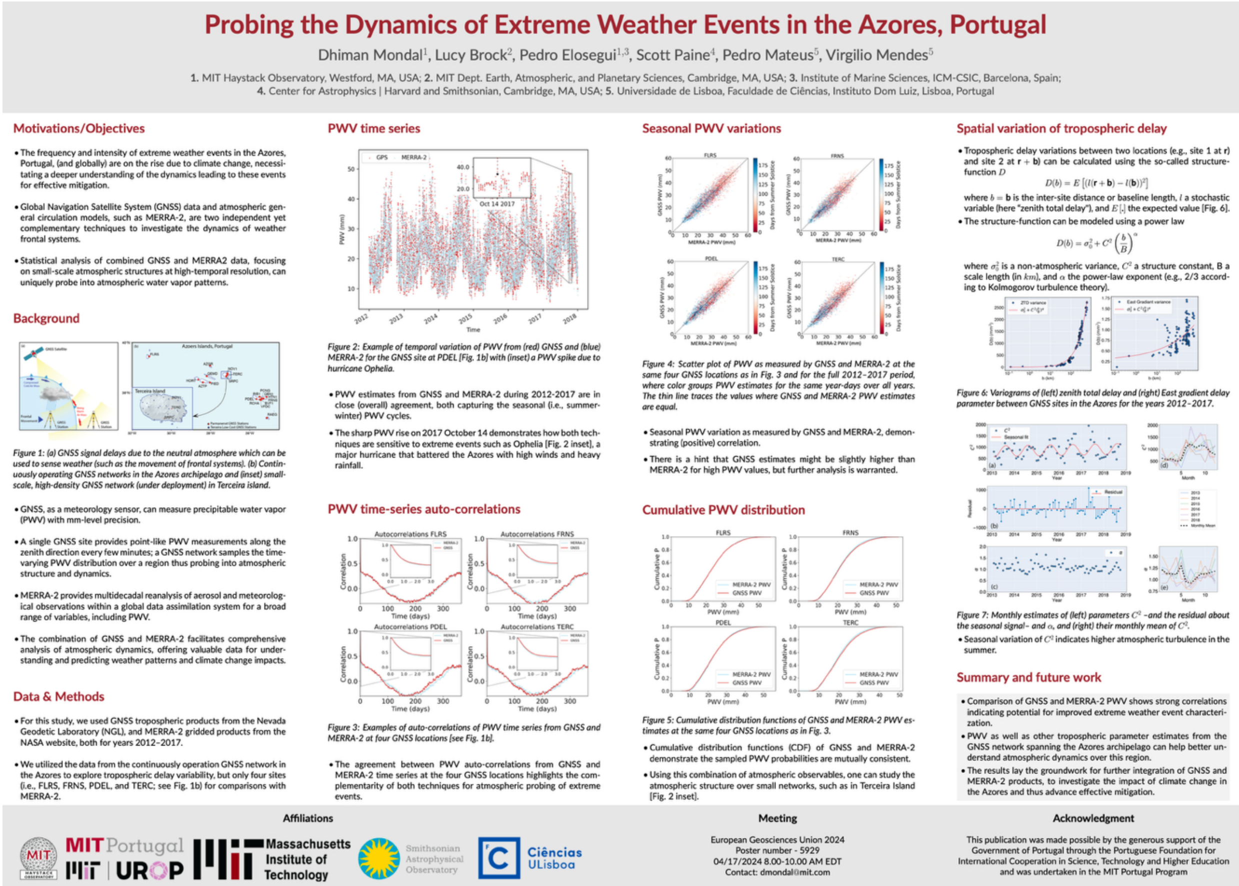
Mateus, P., Mendes, V.B., Miranda, P.M., Mondal, D.R. and Elosegui, P., 2024. *Monitoring Atmospheric Water Vapor Cost-Effectively Using GNSS Tomographic Methods*. In *AGU Fall Meeting Abstracts* (Vol. 2024, No. 336, pp. G33A-336).

Appendix:

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



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



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

Nathra Ramrajvel[1,2], Dhiman Mondal[1], Pedro Elosegui[1,3], Scott Paine[4], Pedro Mateus[5], Virgilio Mendes[5]

1. MIT Haystack Observatory, Westford, MA, USA; 2. MIT Dept. Earth, Atmospheric, and Planetary Sciences, Cambridge, MA, USA; 3. Institute of Marine Sciences, ICM-CSIC, Barcelona, Spain; 4. Center for Astrophysics | Harvard and Smithsonian, Cambridge, MA, USA; 5. Universidade de Lisboa, Faculdade de Ciências, Instituto Dom Luiz, Lisboa, Portugal

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]*.

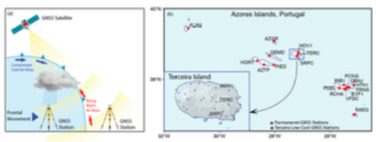


Figure 1*: (a) GNSS signal delays due to the neutral atmosphere which can be used to sense weather (such as the movement of frontal systems). (b) Continuously operating GNSS networks in the Azores archipelago and (inset) small-scale, high-density GNSS network (under deployment) in Terceira island.*

- 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.

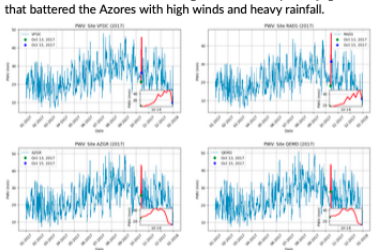


Figure 2*: PWV time-series from (blue) MERRA-2 for four GNSS sites over 2017 with (inset) a (red) PWV spike during hurricane Ophelia.*

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.
- Noteably, 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

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

where $b = \mathbf{b}$ is the baseline length or distance between two stations, l a stochastic variable (here "zenith wet delay"), and $E\,[.]$ 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).

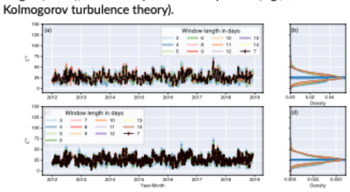


Figure 4: *(a) Multi-day C^2 estimates using non-overlapping, fixed-length time windows from 3 to 14 days, with error bars on the (red circles) weekly estimates, and (c) daily C^2 estimates using overlapping (1-day step), variable-length time windows from 3 to 14 days. (b) and (d) are the respective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

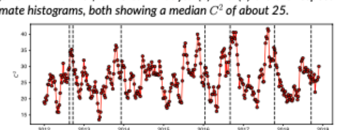


Figure 5: *30-day running mean of C^2 estimates. Vertical bars indicate the timing of the hurricanes in Azores archipelago.*

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

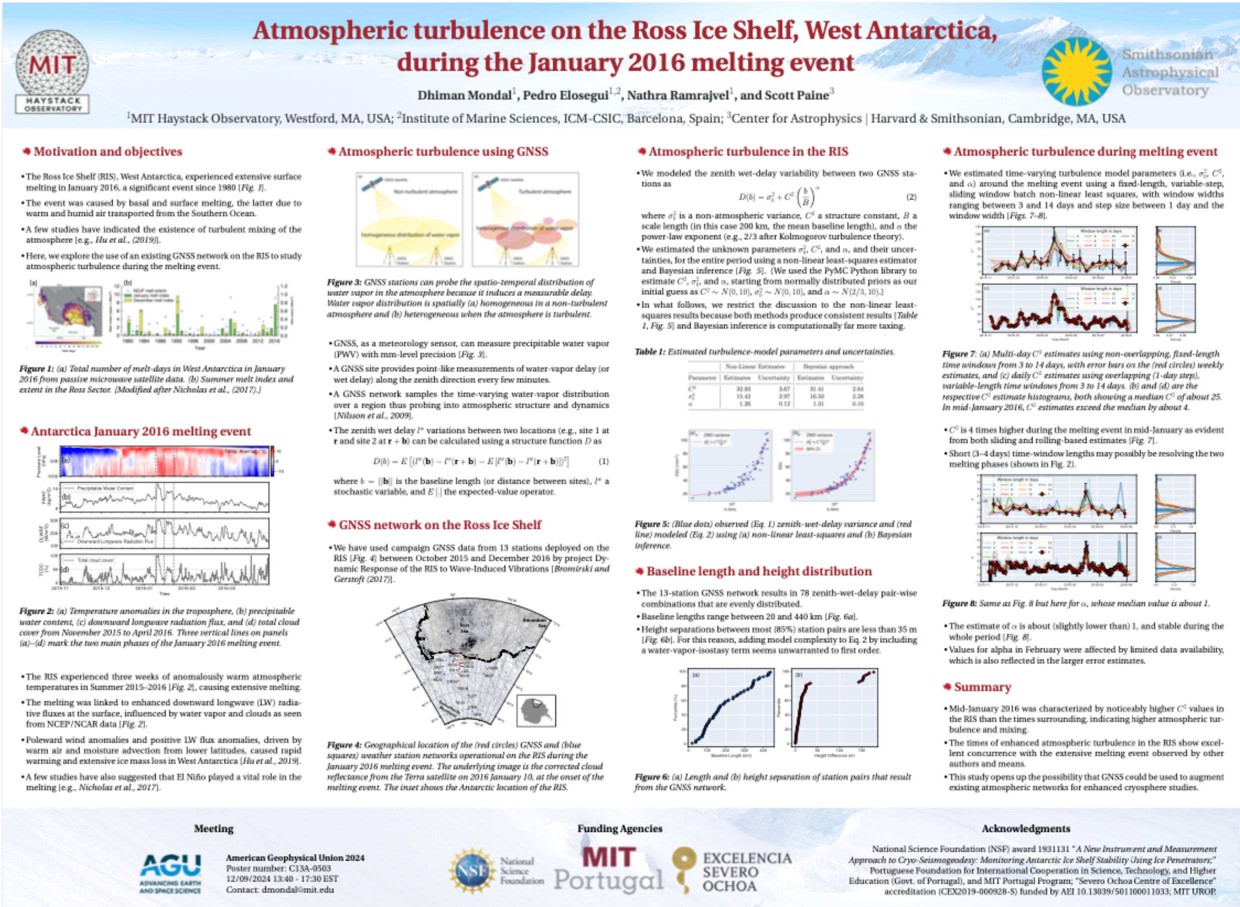
Meeting

European Geosciences Union 2025
05/01/2024 7.00-8.45 AM EDT
Contact: nathra@mit.edu

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 Mondal[1], Pedro Elosegui[1,2], Nathra Ramrajvel[1], and Scott Paine[3]

[1]MIT Haystack Observatory, Westford, MA, USA; [2]Institute of Marine Sciences, ICM-CSIC, Barcelona, Spain; [3]Center 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 Sector. [Modified after Nicholas et al., (2017).]*

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*].

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 l^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

$$D(b) = E\left[\left(l^w(\mathbf{b}) - l^w(\mathbf{r}+\mathbf{b}) - E\left[l^w(\mathbf{b}) - l^w(\mathbf{r}+\mathbf{b})\right]\right)^2\right] \quad (1)$$

where $b = ||\mathbf{b}||$ is the baseline length (or distance between sites), l^w a stochastic variable, and $E[.]$ the expected-value operator.

GNSS network on the Ross Ice Shelf

- We have used campaign GNSS data from 13 stations deployed on the RIS [*Fig. 4*] between October 2015 and December 2016 by project Dynamic Response of the RIS to Wave-Induced Vibrations [*Bromirski and Gerstoft (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 10, at the onset of the melting event. The inset shows the Antarctic location of the RIS.*

Atmospheric turbulence in the RIS

- We modeled the zenith wet-delay variability between two GNSS stations as

$$D(b) = \sigma_0^2 + C^2\left(\frac{b}{B}\right)^{\alpha} \quad (2)$$

where σ_0^2 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_0^2, 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_0^2, and α, starting from normally distributed priors as our initial guess as $C^2 \sim N(0,10)$, $\sigma_0^2 \sim N(0,10)$, 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.

Table 1: *Estimated turbulence-model parameters and uncertainties.*

	Non-Linear Estimates		Bayesian approach	
Parameter	Estimates	Uncertainty	Estimates	Uncertainty
C^2	32.93	3.67	31.41	2.84
σ_0^2	15.42	2.97	16.50	2.28
α	1.26	0.12	1.31	0.10

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

Baseline length and height distribution

- 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-isostasy term seems unwarranted to first order.

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

Atmospheric turbulence during melting event

- We estimated time-varying turbulence model parameters (i.e., σ_0^2, 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*].

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.*

- 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.*

- The estimate of α is about (slightly lower than) 1, and stable during the whole period [*Fig. 8*].
- Values for alpha in February were affected by limited data availability, which is also reflected in the larger error estimates.

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.

Meeting

American Geophysical Union 2024
Poster number: C13A-0503
12/09/2024 13:40 - 17:30 EST
Contact: dmondal@mit.edu

Funding Agencies

Acknowledgments

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