2021-2022 Tongan volcanic eruptions and record rainfall in eastern Australia and New Zealand

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Summary

During late 2021, the Hunga Tonga-Hunga Ha'apai submarine volcano erupted creating a new island which erupted sub-aerially on 15th January, 2022 sending a plume 58 km above sea level penetrating the mesosphere. The study of observation records including satellite data has revealed warming of the ocean-surface layer followed by atmospheric cooling caused by the release of geothermal heat and volcanic materials entering the atmosphere respectively. Environmental factors influencing weather include the development of a relatively 'short' life-span South Pacific Blob; the transfer of large quantities of water vapour from the ocean into the atmosphere; the low-pressure condition on the ocean surface; the formation of clouds; the reduction of solar radiation caused by volcanic materials in the atmosphere; the strengthening of trade winds; the meandering of jet streams; the development of atmospheric rivers, the additional cooling effect of torrential rainfall, and, the switch to La Niña conditions. The record rainfall in eastern Australia and New Zealand and Tropical Cyclone Dovi occurring in February 2022 were both outcomes of atmospheric cooling following the sub-aerial eruption.

Introduction

The Hunga Tonga-Hunga Ha'apai volcano is located in the Kermadec-Tonga trench of the southern Pacific Ocean. A recent study has shown that earlier eruptions during August to December 2019 of at least two submarine volcanoes in Tonga and White Island volcano in New Zealand contributed geothermal heat to form a South Pacific Blob setting a new hottest temperature record for Antarctica on 6th February, 2020.[1] Although the climatic impact of every volcanic eruption is different, sub-aerial volcanic eruptions have a cooling tendency while submarine eruptions have a warming tendency. The present study investigates observation records including satellite data on the role of the initially submarine eruptions of the Hunga Tonga-Hunga Ha'apia volcano in late 2021 which culminated in the millennium by the Volcanic Explosivity Index (VEI) 5 sub-aerial eruption on 15th January, 2022 (Figure 1) as a cause of the record rainfall in eastern Australia and New Zealand to the end of February 2022.

NOAA's GOES 17 and Japan's Himawari 8 satellites were perfectly positioned to observe and document the historic event.[2] The 58 km plume height was two and a half times higher than any thunderstorms ever observed and the atmospheric pressure generated by the eruption circled Earth for several days. Multiple geostationary satellites with sensors detected the travelling pressure waves via temperature changes in mid-level atmospheric water vapour imagery.

Figure 1. Satellite image of the Hunga Tonga Hunga Ha'apai VEI 5 sub-aerial eruption on 15th January, 2022.

Oceanic and atmospheric changes

Initially the Tongan eruptions were submarine resulting in regional ocean warming through the release of geothermal heat and on 15th January, 2022, sub-aerial switching to regional atmospheric cooling driven by volcanic materials entering the atmosphere. Environmental factors influencing weather during the various stages were therefore different. They include the following:

(1) The formation of a relatively 'short' life span South Pacific Blob.
(2) The transfer of large quantities of water vapour from the ocean into the atmosphere.
(3) The low-pressure condition on the ocean surface.
(4) The formation of clouds.
(5) The reduction of solar radiation caused by volcanic materials in the atmosphere.
(6) The strengthening of trade winds.
(7) The meandering of jet streams.
(8) The development of atmospheric rivers.
(9) The additional cooling effect caused by torrential rainfall.
(10) The switch to La Niña conditions.

Hot seawater building up on the ocean-surface layer caused by the submarine eruptions increased the amount of water vapour in the atmosphere, facilitating cloud formation and providing additional energy for tropical cyclones. Figure 2 shows the latent heat flux for February 2022 obtained by the National Centre for Environmental Prediction-National Centre for Atmospheric Research (NCEP-NCAR) reanalysis model compared to the 1981-2010 long-term mean. High values exceeding the long-term average of 135 W/m^2 (over 180 W/m^2) and 45 W/m^2 (over 60 W/m^{i2}) can be observed in eastern Australia (black circled area) and northern New Zealand (white circled area) respectively. The Tongan eruptions increased rainfall in these areas through the input of volcanic aerosols as condensation nuclei, the transfer of large quantities of water vapour from the ocean into the atmosphere and the contribution to cloud formation.

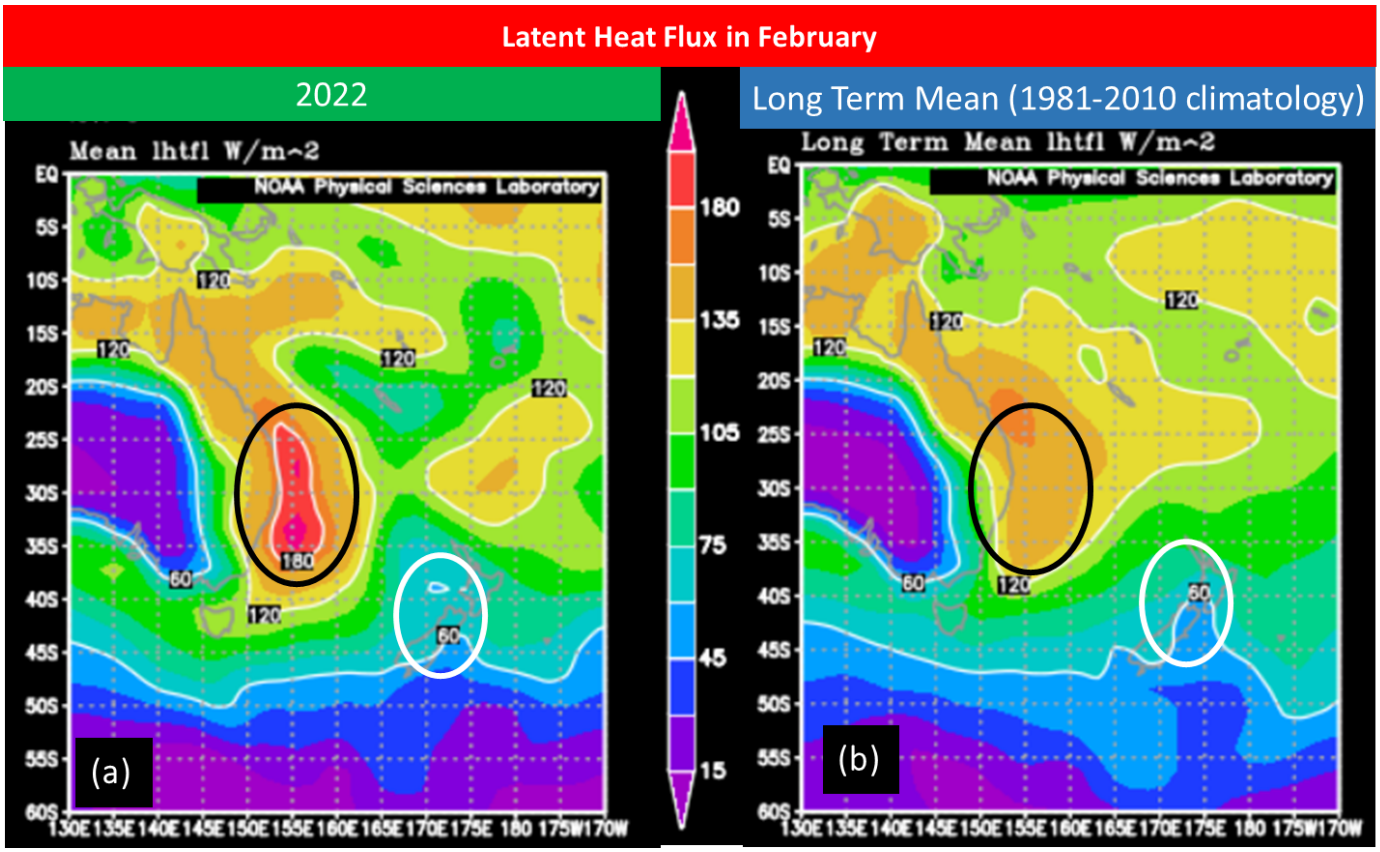


Figure 2. Comparison of latent heat flux in the southwest Pacific Ocean between February 2022 and 1981-2010 long-term mean. Source: NOAA.[3]

Large amounts of ash and gases, including sulphur dioxide and water vapour, were released into the atmosphere during the sub-aerial eruption on 15th January, 2022. Sentinel-5 Precursor (Sentinel-5P) and the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) satellites detected approximately 400,000 tonnes of sulphur dioxide and approximately 7 km thickness of volcanic ash in the stratosphere.[4, 5] Through the Global Ozone Monitoring Experiment-2 (GOME-2) and the Infrared Atmospheric Sounding Interferometer (IASI) from the Meteorological Operational (MetOp) satellite, sulphur dioxide from the eruption was above South Africa and South America in just 10 days with some still remained in the atmosphere above Australia and New Zealand at the end of January 2022.[6]

Since the rising volcanic plume produced by the sub-aerial eruption weakened the temperature gradient, the jet stream became more sinuous. An upper trough caused by jet stream meandering was observed over eastern Australia and New Zealand on 1st and 23rd February, 2022 (Figure 3a-b black circles). In the lower atmosphere, the region ahead of the upper trough favoured air convergence while in the upper atmosphere the opposite air divergence was favoured. The sharp increase in water vapour ahead of the upper trough generated unstable conditions to produce heavy rainfall. Additionally, the upper trough facilitated the development of atmospheric rivers assisting the transportation of water vapour towards eastern Australia and New Zealand (Figure 3c-d black circles). Since 30th January, 2022, a narrow atmospheric river with high values of 50 mm of water vapour was observed to be transported to New Zealand. During the week of 6th-12th February, 2022, the atmospheric rivers became stronger and more water vapour, in excess of 60 mm was delivered to New Zealand. During the week of 20th-26th February,

2022, the atmospheric river weakened, but significant amounts of water vapour approaching 60 mm were still delivered to eastern Australia.

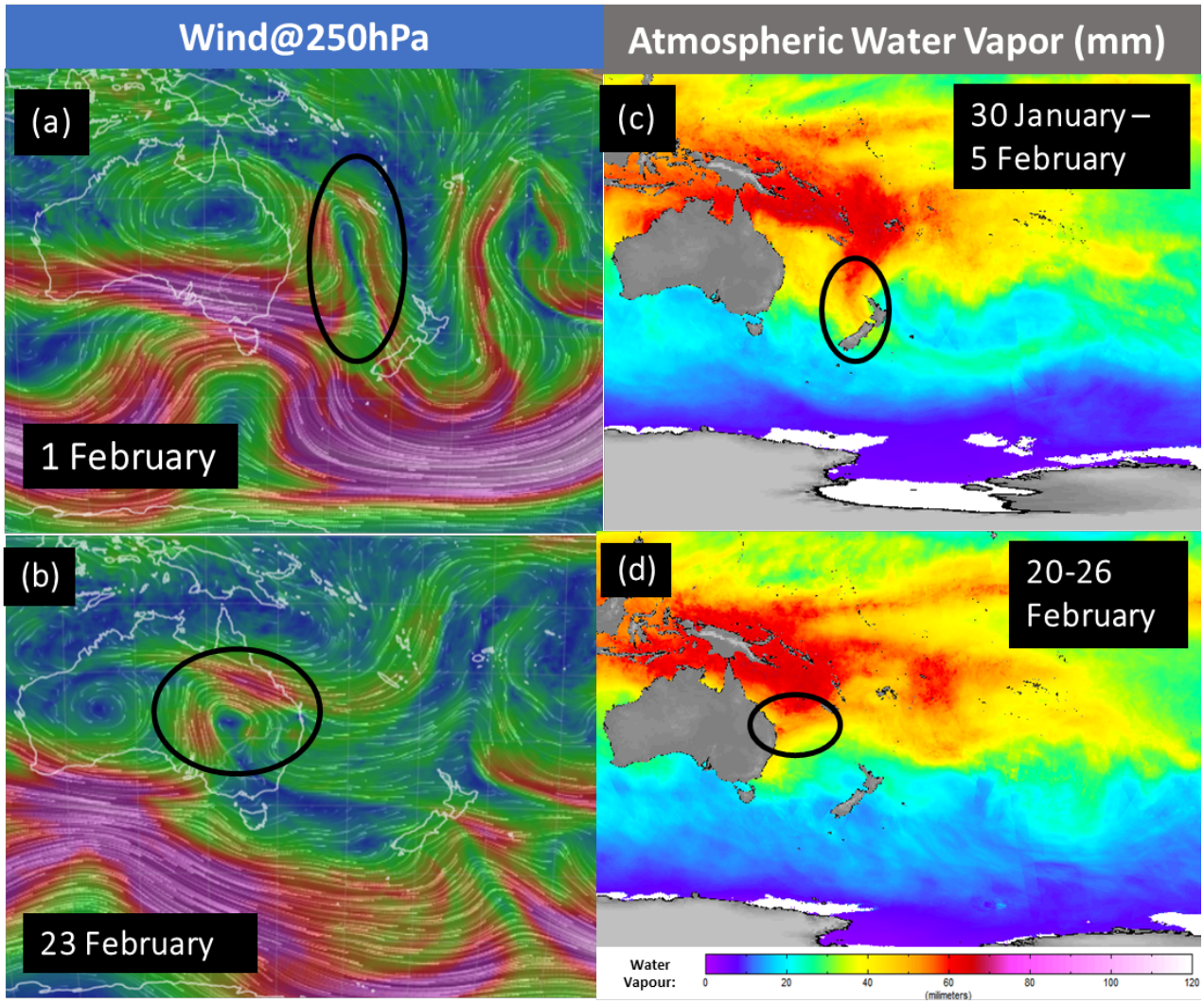


Figure 3. (a-b) Wind pattern at 250hPa on 1st and 23rd February 2022; (c-d) Advanced Microwave Scanning Radiometer-2 (AMSR-2) weekly atmospheric water vapour in mm during 30th January to 26th February, 2022. Source: United States National Weather Service, AMSR-2.[7, 8]

A simplified model of the 2021-2022 Tongan submarine/sub-aerial eruptions is shown in Figure 4.

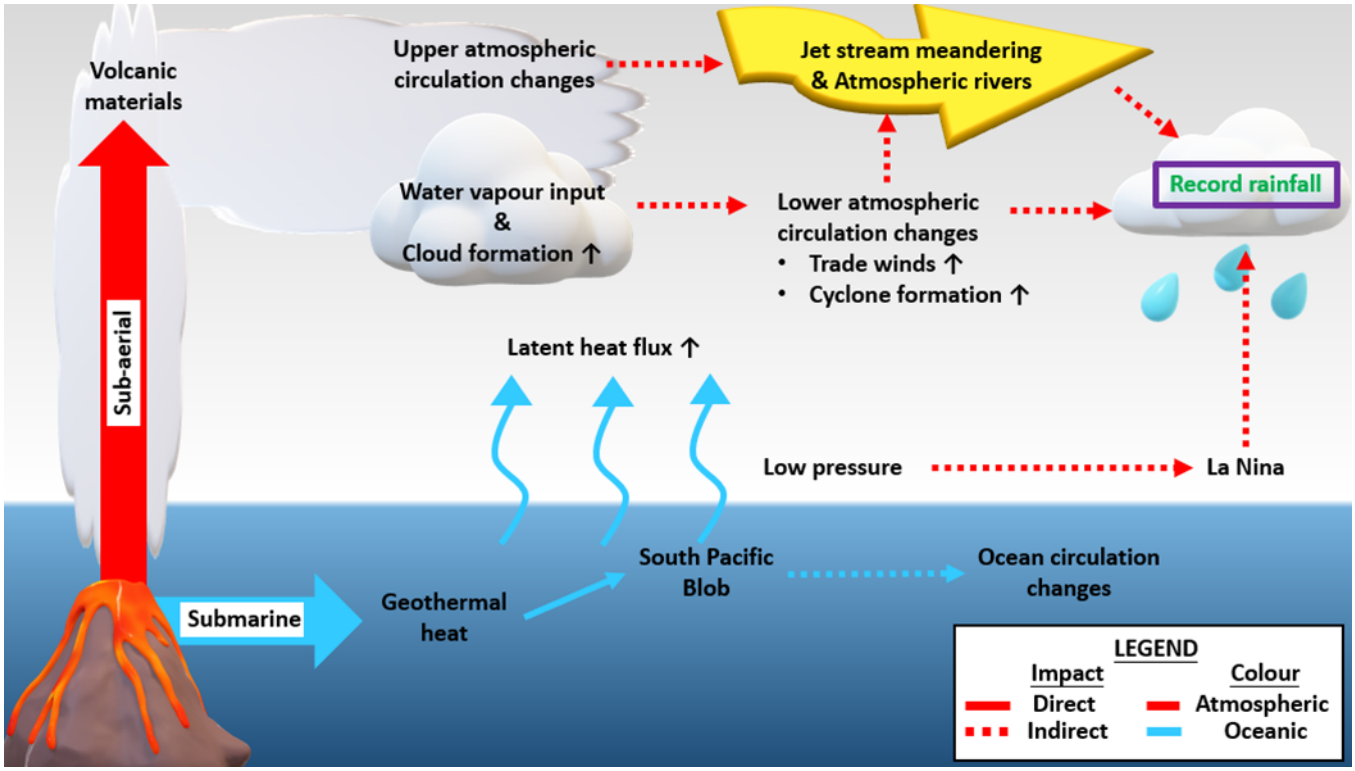


Figure 4. Simplified model of the 2021-2022 Tongan submarine/sub-aerial eruptions.

2021-2022 South Pacific Blob

Based on fortnightly sea-surface temperature records of NOAA's Coral Reef Watch,[9] the development stages of the South Pacific Blob observed from mid-December 2021 to mid-February 2022 (Figure 5) include:

(1) On 15th December, 2021, anomalously hot seawater in the ocean-surface layer already established in the southwest Pacific Ocean.

(2) On 29th December, 2021, a South Pacific Blob connected to Tonga can be observed to be at the hottest east of New Zealand with an arm reaching the coast of South America.

(3) On 15th January, 2022, the core of the South Pacific Blob shifted further eastwards but the arm to the coast of South America was detached.

(4) On 15th February, 2022, the South Pacific Blob continued to extend eastwards with an arm reaching the coast of South America again.

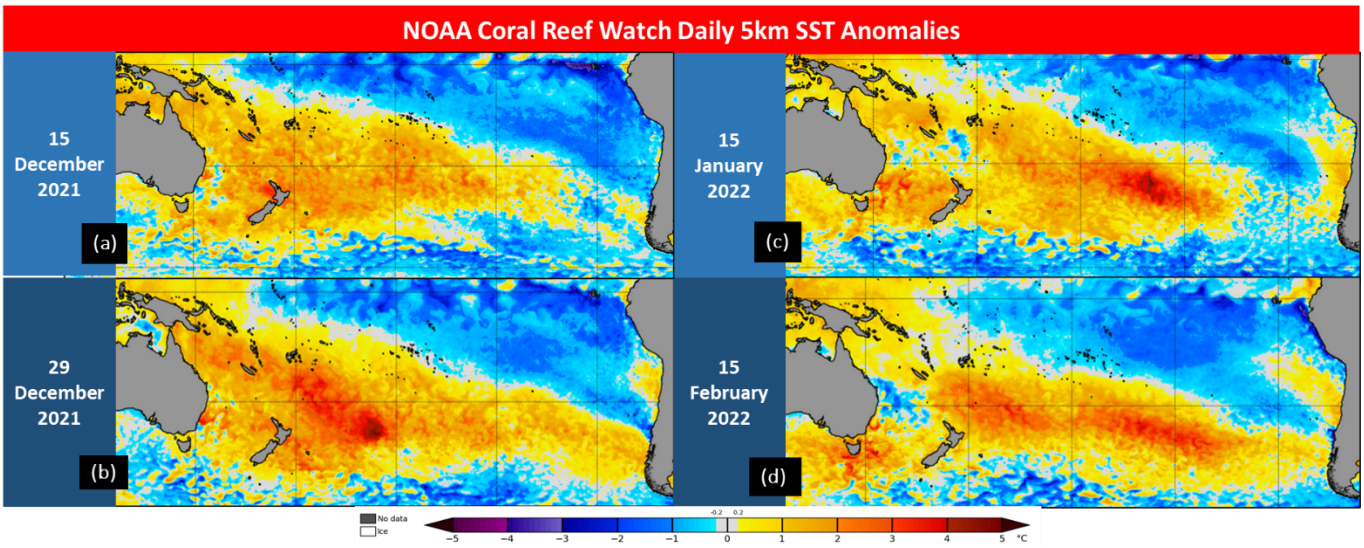


Figure 5. Observations on the development stages of the South Pacific Blob based on sea-surface temperature anomalies at fortnightly intervals from 15th December, 2021 to 15th February, 2022. Source: NOAA Coral Reef Watch.[9]

Observation records of sea-surface temperature anomalies based on NOAA Coral Reef Watch shows that the South Pacific Blob was connected to the submarine eruption of the Tong`a volcano at least since 31st December, 2021. [10] On 16th January, 2022, an approximately 3 km^2 area hot pool greater than 3°C above normal was observed at the Tongan volcano location. Since then, hot seawater was transported by ocean currents into the surrounding waters in a predominantly southeasterly and northwesterly direction. Weekly SST trend data from the NOAA Coral Reef Watch during 30th January to 5th February, 2022 indicated an increase in size of the hot pool with a temperature exceeding 2°C above normal reached a maximum total area of approximately 170,000 km^2 (Figure 6).

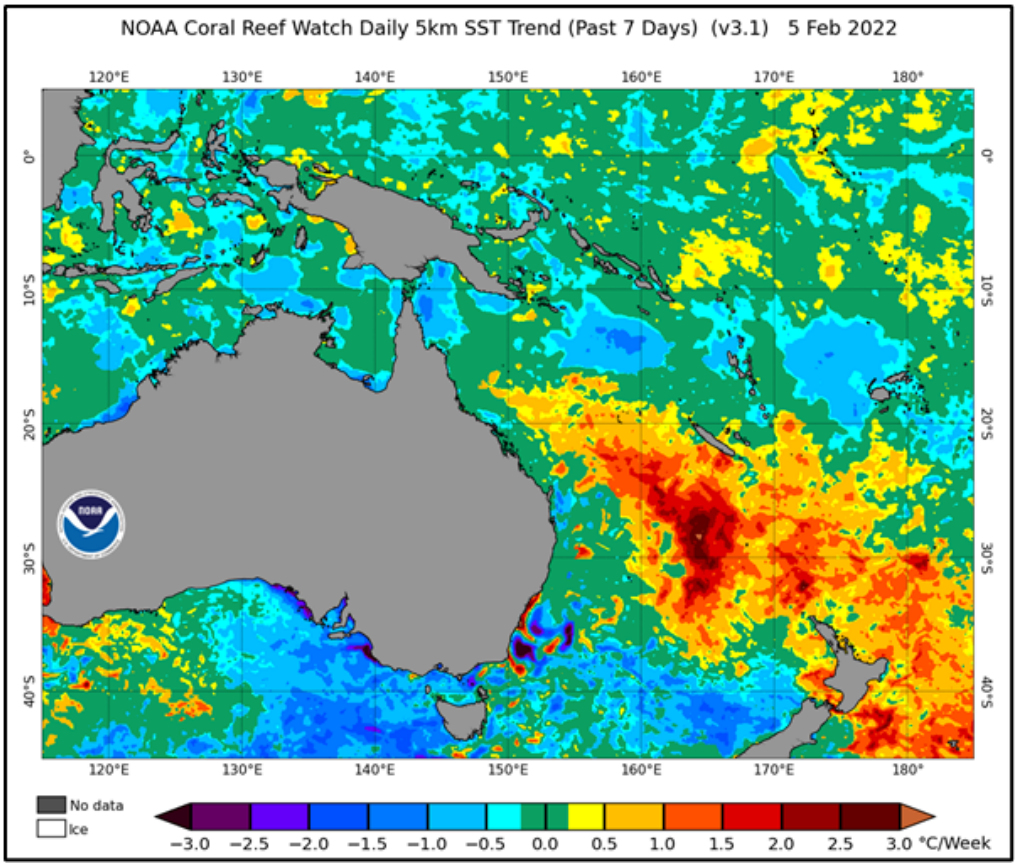
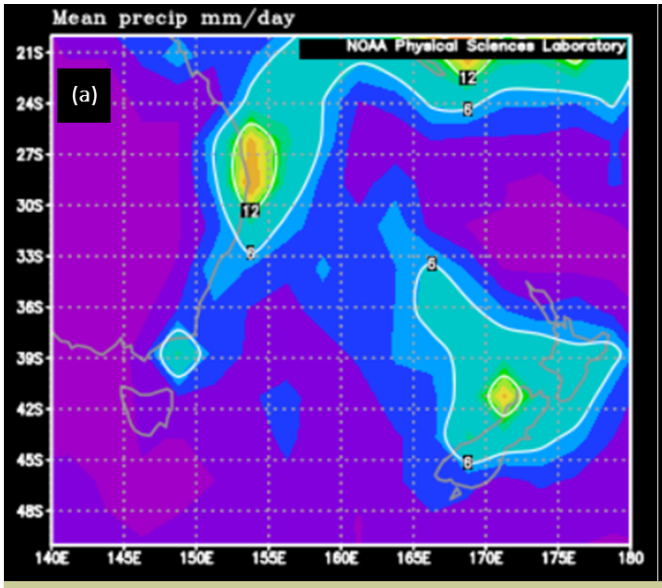


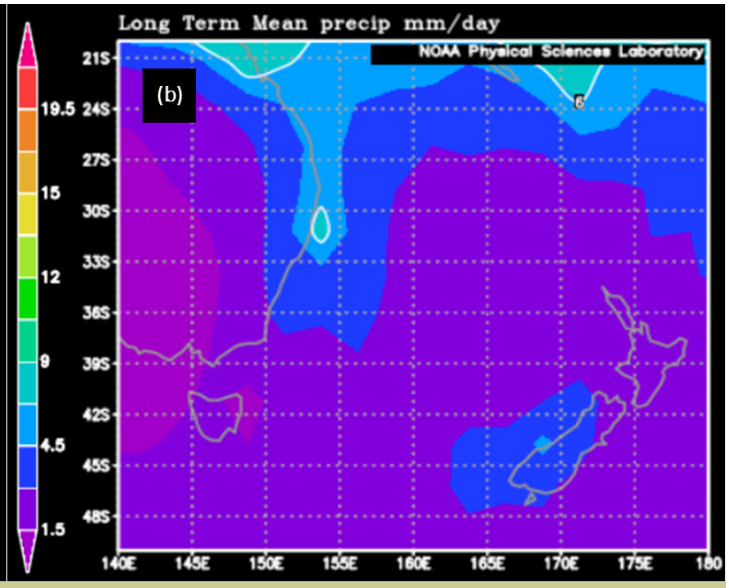
Figure 6. Distribution of sea-surface temperature in the southwest Pacific Ocean during 30th January to 5th February, 2022. Source: NOAA Coral Reef Watch.[9]

Record rainfall in Australia & New Zealand

During the month of February, record rainfall was established at numerous stations in Australia and New Zealand (Figure 7a-b). In comparison to the long-term monthly average, rainfall in eastern Australia exceeded the average value by 5 mm/day while New Zealand exceeded 7 mm/day. These were caused by the combined effects of increased atmospheric moisture content, cloud formation, low-pressure, tropical cyclone, upper trough, solar radiation reduction, atmospheric rivers, trade wind strengthening and the switch to La Niña, all attributed to the Tongan eruption.

Rainfall records were broken at numerous stations. New South Wales in Australia had an anomalously wet February with many new rainfall records (Figure 7c). For the state as a whole, February 2022 rainfall was 29% higher than the 1961-1990 average.[11] Severe flooding occurred in Queensland and New South Wales, with over 58,000 homes flooded between 22nd-26th February, 2022.[12, 13] In New Zealand, Masterton Airport recorded its wettest day with 124 mm/day on 12th February, 2022 while Kelburn in Wellington had its second wettest day since 1939 with 152.5 mm of rain on 13th February, 2022.[14, 15]





(c)

Record highest February daily rainfall

	New record (mm)		Old record		Years of record
Rosebank (Upper Coopers Creek)	701.8	on the 28th	354.2	on the 2nd in 2001	47
Rosebank (Repentance Creek)	620.0	on the 28th	413.4	on the 29th in 1976	65
Uki (Tweed River)	575.0	on the 28th	306.0	on the 2nd in 2001	21
Corndale (Coopers Creek)	539.0	on the 28th	254.0	on the 2nd in 2001	22
Nimbin (Goolmangar Creek)	537.0	on the 28th	155.0	on the 25th in 2004	22
Kunghur (The Junction)	522.0	on the 28th	271.0	on the 2nd in 2001	53
Mullumbimby (Fairview Farm)	520.0	on the 28th	359.0	on the 2nd in 2001	124
Rock Valley (Leycester Creek)	503.0	on the 28th	268.8	on the 2nd in 2001	22
Bentley (Back Creek)	485.0	on the 28th	161.0	on the 2nd in 2001	21
Boat Harbour (Rous River)	438.0	on the 28th	250.0	on the 2nd in 2001	22
Tuncester (Leycester Creek)	437.0	on the 28th	188.0	on the 2nd in 2001	22
North Murwillumbah (Tweed River)	411.0	on the 28th	270.0	on the 2nd in 2001	22
Clunes (Flatley Drive)	394.0	on the 28th	368.0	on the 29th in 1976	61
New Italy (Vineyard Haven)	385.0	on the 28th	140.0	on the 24th in 2004	36
Lillian Rock (Williams Road)	369.0	on the 28th	255.4	on the 2nd in 2001	56
McLeans Ridges (Lascott Drive)	364.8	on the 28th	261.0	on the 2nd in 2001	23
Eungella (Oxley River)	345.0	on the 28th	271.0	on the 2nd in 2001	25
Nashua (Wilsons River)	325.0	on the 28th	250.0	on the 2nd in 2001	22
Whiporie Post Office	297.4	on the 28th	154.8	on the 23rd in 2013	56
Lawrence Road (Pringles Way)	290.4	on the 28th	248.2	on the 24th in 2004	21
Brays Creek (Misty Mountain)	287.0	on the 28th	275.3	on the 18th in 1956	72
Yamba Pilot Station	274.4	on the 28th	270.5	on the 21st in 1954	144
Grafton Research Stn	252.0	on the 28th	136.0	on the 23rd in 2013	33
Casino Airport AWS	240.2	on the 28th	219.0	on the 2nd in 2001	28
Ballina Airport AWS	195.4	on the 28th	188.0	on the 2nd in 2001	30
Wyong (Olney Forest)	160.0	on the 23rd	146.0	on the 9th in 2020	22
Lismore Airport AWS	146.8	on the 24th	112.8	on the 7th in 2020	21

Record highest February total rainfall

	New record (mm)	Old record		Years of record	Average for February
Rosebank (Upper Coopers Creek)	1199.6	793.0	in 1976	45	278.9
Rosebank (Repentance Creek)	1144.8	970.7	in 1976	64	277.0
Uki (Tweed River)	1143.0	633.0	in 2020	20	295.9
Bentley (Back Creek)	1035.0	318.0	in 2001	20	186.0
Kunghur (The Junction)	1022.0	583.0	in 2020	51	214.9
Boat Harbour (Rous River)	1001.0	786.0	in 2020	22	289.8
Nimbin (Goolmangar Creek)	991.0	505.0	in 2020	22	224.7
Mullumbimby (Fairview Farm)	977.2	946.5	in 1956	119	243.8
Corndale (Coopers Creek)	977.0	482.0	in 2020	22	225.5
Rock Valley (Leycester Creek)	909.0	472.6	in 2001	22	205.1
North Murwillumbah (Tweed River)	876.0	645.0	in 2020	22	253.4
Tuncester (Leycester Creek)	861.0	453.0	in 2020	22	193.6
Eungella (Oxley River)	860.5	571.5	in 2020	24	232.0
Clunes (Flatley Drive)	852.1	775.0	in 1976	59	213.7
Lillian Rock (Williams Road)	814.0	513.0	in 1971	56	236.2
McLeans Ridges (Lascott Drive)	785.3	506.2	in 2020	23	215.6
Nashua (Wilsons River)	780.0	563.0	in 2020	22	243.5
New Italy (Vineyard Haven)	754.6	515.3	in 2020	39	182.2
Green Pigeon (Morning View)	728.4	614.0	in 2001	54	244.7
Whiporie Post Office	614.6	495.6	in 1976	56	165.7
Casino Airport AWS	573.4	358.2	in 2001	28	162.5
Grafton Research Stn	502.4	451.6	in 1954	66	138.8
Baryulgil (Clarence River)	448.4	324.0	in 2021	20	150.7
Wyong (Mount Elliot)	446.0	302.0	in 2008	21	158.4
Collaroy (Long Reef Golf Club)	419.0	352.6	in 2020	36	140.6

Highest February total rainfall for at least 20 years

	Observed (mm)	Most recent higher		Average for February
Brays Creek (Misty Mountain)	743.0	748.6	in 1954*	228.2
Old Koreelah (McPherson)	238.6	303.0	in 1976*	116.1
Tabulam Post Office	396.8	455.0	in 1976*	144.7
Yamba Pilot Station	549.0	558.2	in 1976*	163.2
Drake (Village Resource Centre)	370.1	530.8	in 1976*	160.7
Randwick (Randwick St)	422.1	643.5	in 1990	117.1
Rose Bay (Royal Sydney Golf Club)	408.8	613.8	in 1990	125.4
Black Swamp (Maxwell)	285.8	300.8	in 1997*	115.6
Tabulam (Muirne)	436.8	460.6	in 2001	188.5
Wilsons Downfall	372.6	414.6	in 2001	159.1

Figure 7. February precipitation rates for eastern Australia and New Zealand in (a) 1981-2010 average and (b) 2022; (c) Selected weather stations in New South Wales, Australia with new February rainfall record. Source: Australian Bureau of Meteorology and NOAA.[11, 16]

Tropical Cyclone Dovi

The formation of Tropical Cyclone Dovi was fueled by the southern hemisphere summer sun assisted by the geothermally heated ocean surface layer through the Tongan submarine eruptions. On 5th February, 2022, a

tropical depression formed in the northern Coral Sea and moved rapidly eastwards into the southwestern Pacific Ocean. On 8th February, 2022, due to the presence of the South Pacific High associated with the strengthening of the upper ridge and caused by the jet stream meandering, the depression changed to a southerly course before strengthening on 9th February, 2022 into Tropical Cyclone Dovi" (Figure 8). Although Dovi weakened into a depression on 12th February, 2022, it contributed significantly to the record rainfall in New Zealand.

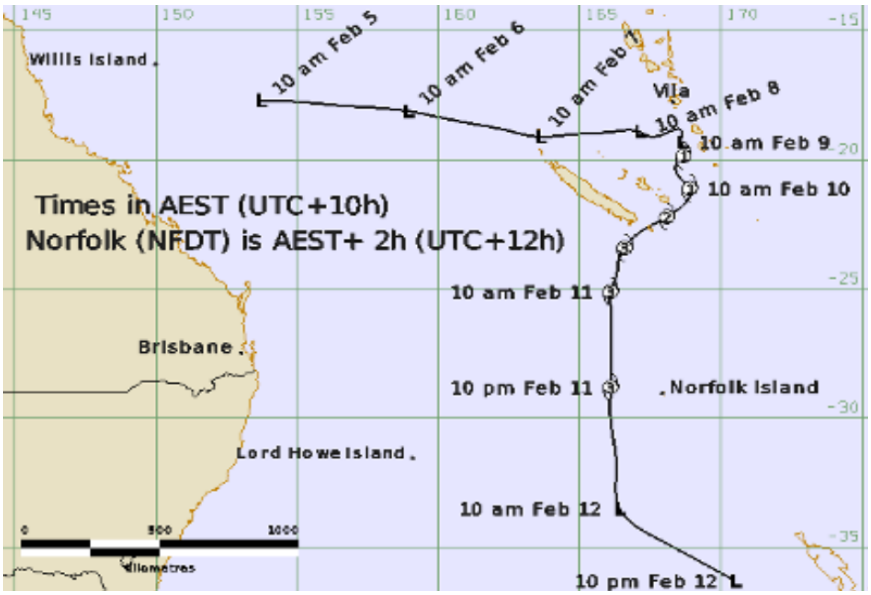


Figure 8. Track of tropical cyclone Dovi. Source: Australian Bureau of Meteorology.[11]

Conclusions

The 2021-2022 Hunga Tonga Hunga Ha'apai volcanic eruptions had an underestimated natural role in climatic change. This study has shown that the record rainfall in Australia and New Zealand during February 2022 following the large sub-aerial eruption on 15th January, 2022 including the development of Tropical Cyclone Dovi was the result of the switch to atmospheric cooling triggered by the sub-aerial eruption. This is supported by observation records including satellite data.

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Alvin Wong graduated with an MSc Earth Systems Science degree in 2018 at the Institute of Space and Earth Information Science, Chinese University of Hong Kong in 2018 and was awarded the Dean's Honours list. His research project on geothermal heat in decadal Arctic sea-ice changes was awarded the top prize in the class.

Wyss Yim is a retired professor at the University of Hong Kong where he spent 36 years until retirement teaching civil engineering, geosciences and environmental management students, and helped found the

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