Externally forced and internal variability in multi-decadal climate evolution

During the last 150 years, the increasing atmospheric concentration of anthropogenic greenhouse gases has been the main driver of climate change. Superimposed on the man-made global warming trend, however, natural variability modulates the climate record on time scales from years to several decades. Natural climate variability encompasses internal variability – spontaneously generated by processes and feedbacks within the climate system, and externally forced variability – caused, for example, by changes in solar activity and volcanic eruptions. To investigate natural variability, the focus of scientific research is often extended back in time to include many centuries of the pre-industrial past, where anthropogenic impacts are minor. Using the Earth System Model of the Max Planck Institute for Meteorology (MPI-M), Davide Zanchettin and his colleagues demonstrated the role of strong volcanic eruptions as major driver of climate variability during the pre-industrial millennium. The scientists explored why the changes induced by these eruptions last much longer in the climate system than the short-lived presence of volcanic particles in the atmosphere. A multitude of simulations reveals that individual realizations of a volcanic event can diverge substantially depending on background conditions. Accurate knowledge of these conditions is therefore instrumental to improve the prediction of climate events triggered by strong volcanic eruptions on decadal or longer time-scales.

Impact of strong volcanic eruptions

During a major volcanic event, if the column of emitted volcanic gas penetrates the stratosphere, it soon turns into a thin aerosol cloud that distributes in the lower stratosphere. There, it persists for a couple of years and scatters part of the incoming solar radiation back to space, which results in the most known direct climatic effect of volcanic eruptions: surface cooling. At the same time, however, the volcanic aerosol cloud also induces indirect dynamical climate responses, affecting processes that govern the long-term evolution of the climate system. Therefore, the signature of strong volcanic eruptions on the climate can persist well beyond the duration of the short-lived radiative forcing.

Coupled climate simulations have corroborated the idea that strong volcanic eruptions can influence the establishment and evolution of decadal and even longer climate anomalies. However, early results left gaps of knowledge concerning how robust these long-term responses are to eruptions of different characteristics and how the response depends on the background climate conditions (i.e. the mean state of the climate, or the presence of additional forcing factors).

In the framework of the MiKlip project, Davide Zanchettin and his colleagues at MPI-M tried to fill these gaps of knowledge by answering three research questions:

Do strong tropical volcanic eruptions robustly affect simulated climate variability on decadal timescales? (1, 2)

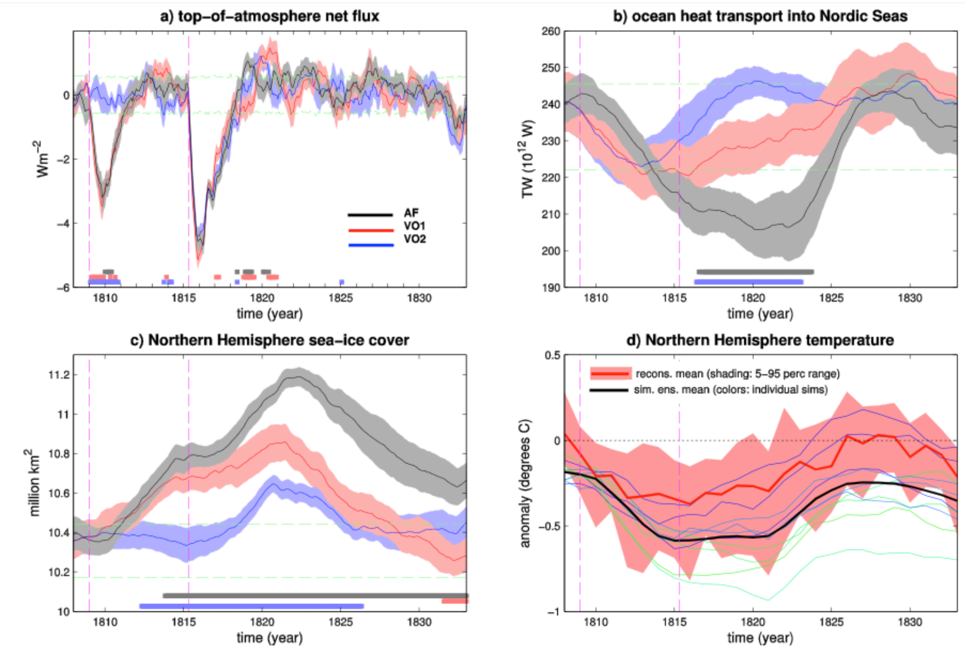
Do climate reconstructions corroborate the existence of decadal climate variability driven by strong volcanic eruptions? (3, 4, 5)

Do background conditions affect the decadal climate response to strong volcanic eruptions? What are the limits of reproducibility of historical events? (6)

In a series of papers, Davide Zanchettin and his collaborators analyzed an ensemble of several climate simulations that allowed them to assess a multitude of strong tropical volcanic eruptions in the last millennium. They identified a typical climate response in the North Atlantic/European sector (1,2) and proposed a mechanism for such response, which includes a decadal-scale feedback loop between the large-scale atmospheric circulation, Arctic sea ice, and the oceanic circulation and its associated heat transports in the Atlantic Ocean. They found "real-world" signatures compatible with such mechanism in multi-centennial reconstructions of North Atlantic and European seasonal climate and labeled the phenomenon „delayed winter warming" (3).

However, the scientists realized that while responses such as the delayed winter warming emerge on average, individual realizations can vary substantially due to different background or initial conditions. Simulating even the same eruption in the same model system with slightly differing initial conditions can result in diverging pathways of climate evolution.

In order to tackle this uncertainty in a systematic way, they used sensitivity experiments with the coupled MPI-M climate model ECHAM5/MPIOM, where they created simulation ensembles with different climate histories before the eruption and changed the magnitude of other forcing factors acting around the time of the eruption (5). They chose the 1815 Tambora eruption as a case study, as it is the strongest historical eruption, associated to the „year without a summer". Moreover, it occurred only six years after another very strong eruption (1809) and coincided with the Dalton minimum of solar activity. The three ensembles – a realistic full-forcing ensemble, a volcanic forcing-only ensemble, and a Tambora-only ensemble (cancelling the effects of the 1809 eruption) - show indistinguishable forced top-of-atmosphere net radiative imbalances for the Tambora eruption (fig. 1 a), but they differ significantly in the magnitude and coherence of post-Tambora decadal climatic signals (fig. 1 b, c).



Panels a-c: Evolution of key climate quantities around the Tambora eruption in three simulation ensembles differing in the initial state and in the applied forcing (black/grey: all-forcing (AF), red/pink: volcanoes only (VO1), dark blue/light-blue: all forcing but excluding the 1809 eruption (VO2)). Lines denote the ensemble mean and the shading envelope is an estimate of the standard error of the mean. Green dashed lines: Estimate of internal variability in the unforced control experiment. Bottom rectangles indicate periods when there is a significant difference between an ensemble (color same as for time series plots) and the other two. Panel a: Simulated global-average top-of-atmosphere net radiative anomalies (a: 3-month smoothing), Panel b: ocean heat transport into the Nordic Seas (61-months smoothing). Panel c: Arctic sea-ice cover (61-month smoothing). Panel d: Annual Northern-Hemisphere-average surface air temperature (land and ocean) evolutions around the 1815 Tambora eruption from reconstructions (red line and shading) [5] and from the all-forcing (AF) climate simulations (11-year moving average). Blue to green lines are individual simulations. Anomalies are with respect to the 1799–1808 period. In all panels, vertical dashed lines indicate the 1809 and Tambora eruptions. Each ensemble consists of 10 simulations differing in the initial state.

For instance, the experiments clarified that the Tambora alone would not have been able to induce significant anomalies in the North Atlantic and in the Arctic sectors lasting until the next big eruptions in the mid 1830s (fig. 1 d). They do so under full forcing conditions, as the colder conditions induced by the forcing history, including the 1809 eruption and the Dalton Minimum allow for stronger positive feedbacks between reduced poleward ocean heat transport in the North Atlantic and increased Arctic sea ice. So, background conditions, and especially the ocean state, largely constrain the simulated decadal responses to the Tambora eruption by modulating the strength of the feedbacks initiated by the imposed forcing. This ultimately demonstrated that accurate knowledge of the initial climate state and of other external forcing acting around a given eruption is essential for accurately simulating the eruption‘s climatic imprint on decadal timescales.

In practice, these results demonstrate that no individual realization can be expected to match the reconstruction, owing to the uncertainty in the background conditions. This uncertainty is particularly large for the time before the instrumental period and represents a serious obstacle to identifying the decadal-scale climatic consequences even of very strong external perturbations. Of course, the findings by Zanchettin and co-workers have also strong implications for the predictability of the climatic repercussions of future volcanic events.

The work of the group also focused on regions where the decadal climatic imprint of volcanoes is less robust, like in the Pacific/North American sector (6). These regional uncertainties demonstrate that there is still much to be understood about volcanically-forced climate variability in order to improve climate model simulations of past climate. To this regard, significant progress is envisaged by the international initiative VolMIP (Model Intercomparison Project on the climate response to Volcanic forcing, www.volmip.org), co-chaired by Davide Zanchettin, Claudia Timmreck (MPI-M) and Myriam Khodri (IPSL, Paris). VolMIP defines a protocol for idealized volcanic-perturbation experiments to be implemented in different climate models. By subjecting different models to the same volcanic forcing and under similar background conditions, this coordinated modeling activity will separately address the individual sources of uncertainty in the simulated climate response to strong volcanic eruptions, including differences in the model’s characteristics, applied forcing and initial state.

Conclusions

Under indistinguishable imposed volcanic forcing but different background conditions (initial conditions and presence and magnitude of additional forcings), individual realizations within an ensemble of simulations can significantly differ in the magnitude and coherence of post-eruption decadal oceanic signals.

Uncertainty in background conditions complicates the assessment of simulated decadal climate responses to strong tropical volcanic eruptions and, consequently, the predictability of decadal climate evolutions after major volcanic events. Potentially, this explains some discrepancies between simulations and reconstructions of the climate of the last millennium.

More information

The BMBF-funded project MiKlip, which is coordinated at the Max Planck Institute for Meteorology (MPI-M) investigates how to turn the potential for decadal climate prediction into realized predictive skill.

Publications

IPCC-AR5 – www.ipcc.ch

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