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PERSPECTIVE

Might stratospheric variability lead to improved predictability of ENSO events?

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The El Niño/Southern Oscillation (ENSO) is the dominant mode of oceanic variability on interannual timescales. It is characterized by variations of sea surface temperatures in the equatorial central and eastern Pacific—warmer during El Niño and colder during La Niña—that have been linked to persistent regional and global atmospheric anomalies [1–3]. These substantial impacts must be anticipated and planned for in order to mitigate deleterious effects on society and ecosystems, but only after a forecast of ENSO has been issued can such mitigative action begin. While some ENSO events are predictable up to 2 years in advance [4, 5], most ENSO events are only predictable after the 'barrier' in the boreal spring immediately before the event has been crossed.

Traditionally, ENSO events are forecasted using coupled ocean-atmosphere general circulation models in which chemical processes in the stratosphere are not explicitly considered. A recent letter by Xie *et al* [6] suggests that this may lead to an underestimation of the predictability of ENSO events, as Arctic stratospheric ozone anomalies precede, and likely force, ENSO variability.

The letter by Xie *et al* [6] first shows that over the historical record, there is a statistically significant correlation between Arctic stratospheric ozone and the Niño 3.4 index twenty months later: the correlation is −0.35 when all calendar months are considered, and rises to −0.57 when the seasons with maximum variability are considered (i.e. the correlation of spring ozone with winter ENSO variability 20 months later). Additional, causal, evidence is provided by model simulations with the Community Earth System Model: while the model has no skill at reproducing the historical timing of specific ENSO events (as expected due to misalignment in the stochastic forcing of ENSO), imposing observed Arctic stratospheric ozone in the model acts as a pacemaker for the ocean-atmosphere coupled system: several strong El Niño events are successfully simulated, and the correlation between the observed and the simulated Niño 3.4 index is statistically significant (correlation of 0.42).

How does Arctic stratospheric ozone affect ENSO? The authors argue that anomalous Arctic ozone, through its effect on absorbed incoming solar radiation, leads to an anomalously warm or cold Arctic lower stratosphere. It is well known that anomalies in lower stratospheric temperature can affect tropospheric storm tracks, though the precise mechanism has not yet been nailed down [7, 8]. (It is also possible that the mechanism relevant to ozone may differ from that associated with more conventional coupling between stratospheric variability and the North Atlantic Oscillation, as the sea level pressure anomaly pattern in figure 5b of Xie *et al* [6] bears no resemblance to the North Atlantic Oscillation.) Arctic stratospheric ozone appears to be associated with sea level pressure variability as far equatorward as the subtropical North Pacific, and after these sea level pressure anomalies are formed and then sustained by ozone anomalies which decay slowly (the autocorrelation of Arctic stratospheric ozone in SWOOSH v2.5 [9] at a lag of two months is 0.70), they can imprint on the oceanic mixed layer. It is well known that anomalies in the mixed layer of the central subtropical Pacific can force ENSO events the following year via the seasonal footprinting mechanism [10].

There is still much to learn before this chain of events can be fully understood. First, it is not clear why the maximum impact on ENSO variability is apparent only 20 months after the Arctic stratospheric ozone anomalies, as the seasonal footprinting mechanism connects the development of an ENSO events in summer to midlatitude atmospheric variability the previous winter [10], and Arctic stratospheric anomalies impact surface variability within a month [11]. It is possible that the midlatitude SST anomaly forced by the Arctic ozone is initially stored beneath the surface and is then reentrained into the mixed layer when it deepens again in the following winter (i.e. winter-to-winter recurrence [12–14]), though whether this effect can account for the apparent 20-month lag needs to be investigated. Second, El Niño events are often followed by La Niña events (and vice versa), such that the autocorrelation of the NDJF seasonal mean Niño 3.4 index at a lag of two years is −0.32 over the period 1979/1980 through 2015/2016 in the ERSST v4 dataset [15]. As anomalies in Arctic ozone are forced, in part, by ENSO events, part of the apparent relationship found by the authors reflects internal oceanic/tropical atmospheric processes and not stratospheric variability. Third, and relatedly, previous work has shown that anomalies in North Pacific SSTs force anomalies in Arctic stratospheric ozone (as the authors themselves note; [16]), and so model experiments of the type Xie *et al* [6] perform are necessary in order to establish that the extratropical Pacific SST anomalies are forced by the Arctic stratospheric ozone anomaly and not vice versa. As the mechanism whereby this process occurs can only be isolated with models, it is crucial that similar experiments are performed with other models in order to assess robustness.

Assuming this connection between Arctic stratospheric ozone and ENSO is demonstrated to be robust and the timing of the connection is better understood, Arctic stratospheric ozone may serve to enhance predictive skill of ENSO at leads in which current models are generally not skillful. Empirical and statistical models of ENSO could incorporate Arctic stratospheric ozone as a predictor, while dynamical coupled ocean-atmosphere models could make sure to assimilate observed ozone concentrations at the start of model integrations (or even better, compute ozone concentrations interactively by adding stratospheric chemistry to their models). Either way, the letter of Xie *et al* clearly demonstrates that oceanic, tropospheric, and stratospheric are all tightly coupled, and that research focusing on connections among these regions can lead to novel conclusions.

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