A first look at ENSO in CMIP5

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Introduction

The El Niño–Southern Oscillation (ENSO) is a naturally occurring fluctuation that originates in the tropical Pacific region with severe weather and societal impacts worldwide (McPhaden et al. 2006). Despite considerable progress in our understanding of the impact of climate change on many of the processes that contribute to ENSO variability, it is not yet possible to say whether ENSO activity will be enhanced or damped, or if the frequency of events will change in the coming decades (Vecchi & Wittenberg 2010, Collins et al. 2010). As changes in ENSO have the potential to be one of the largest manifestations of anthropogenic climate change, this status has profound impacts on the reliability of regional attribution of climate variability and change.

One major reason for our lack of understanding is that, as ENSO involves a complex interplay of numerous oceanic and atmospheric processes, accurately modelling this climate phenomenon with Coupled Global Climate Models (CGCMs), and understanding, anticipating, and predicting its behaviour on seasonal to decadal and longer time scales still pose formidable challenges (Guilyardi et al. 2009a, Wittenberg 2009).

We here presents the first assessment of basic ENSO properties in control simulations of CMIP5 and a comparison with CMIP3. We use the metrics as developed within the CLIVAR Pacific Panel, which assess both the tropical Pacific mean state and interannual properties. The 4 ENSO metrics encompass ENSO amplitude (Niño3 SST std dev), structure (Niño3 vs. Niño4 amplitude), frequency (RMSE of Niño3 SSTA spectra) and heating source (Niño4 precipitation std dev). The other metrics deal with SST, zonal wind stress, precipitation and surface heat flux mean state and annual cycle (Guilyardi and Wittenberg 2010). We also take a preliminary look at simulations with increasing greenhouse gases (1%/year CO_2 increase and abrupt $4xCO_2$ idealised scenario) to examine if there are any robust signals of changes in ENSO in the new CMIP5 models.

We use multi-century pre-industrial simulations for both CMIP3 and CMIP5 as required to ensure statistical robustness (Wittenberg 2009, Stevenson et al. 2010). Simulation lengths are 300 years (but for MIROC-ESM-CHEM, 255 years and HadGEM2CC, 240 years). The analysis in Figs 1 and 2 is presented per modelling centre to also assess progress (see Table 1 for official CMIP model names). Precise CMIP5-variables used in the analysis are detailed in the figure captions. Observations or reanalysis used for reference include HadISST1.1 (Rayner et al. 2003, years 1900-1999), ERA40 (Uppala et al. 2005), CMAP (Xie and Arkin 1997) and OAFlux (Yu and Weller 2007).

Modelling centre	CMIP3 model(s)	CMIP5 model(s)
BCC	n/a	BCC-CSM-1
CCCma	CGCM3.1	CanESM2
CNRM	CNRM-CM3	CNRM-CM5
CSIRO	CSIRO-Mk3.0	CSIRO-Mk3.6
GFDL	GFDL2.0 GFDL2.1	GFDL-ESM2M
GISS	GISS-AOM GISS-EH GISS-ER	GISS-E2-H GISS-E2-R
IAP	FGOALSg1.0	n/a
INM	INM-CM3.0	INM-CM4
IPSL	IPSL-CM4	IPSL-CM5A-LR IPSL-CM5A-MR
MIROC	MIROC3.2-MR MIROC3.2-HR	MIROC5 MIROC-ESM MIROC-ESM-CHEM
MOHC	HadCM3 HadGEM1	HadGEM2-CC HadGEM2-ES
MPI	ECHAM5/MPI-OM	MPI-ESM-LR
MRI	MRI-CGCM2.3.2	MRI-CGCM3
NCC	-	NorESM1-M

Table 1: CMIP3 and CMIP5 official model names per modelling centre.

Has ENSO performance in CGCMs improved since CMIP3 ?

A preliminary analysis of the metrics in Fig. 1 first shows that the range of modelled ENSO amplitude in CMIP5 (red dots in Fig. 1a) is reduced by about half compared to CMIP3 (blue dots). This is a clear improvement over the CMIP3 ensemble where this diversity was larger than could be explained by observational variability/uncertainty. Although we note that this is a preliminary result as not all modelling groups have submitted output at this stage and the spread of the CMIP5 models could still go up.

The ENSO amplitude, as measured by SST standard deviation, was too large in the central/west Pacific in CMIP3 CGCMs (Niño4 region, 0.8 °C compared to 0.65 °C in observations) and this has also improved in CMIP5 (0.6 °C). Nevertheless there is still the occasional model with spuriously more variability in the west than in the east Pacific (CSIRO-Mk3.6 in CMIP5, CCCma-CGCM3.1 in CMIP3). About half of the centres for which data is available for both CMIP3 and CMIP5 (11 centres) show an improvement in ENSO amplitude while the rest show no change or degradation.

The ENSO spectra metric (Fig. 1g) also shows an improved picture in CMIP5 when compared to CMIP3 even at the individual model level. As this metric is sensitive to slight shifts in modelled ENSO spectra and the real-world spectra may not be well constrained by the short observational record this result much be taken with caution. The heating source associated with ENSO, as measured by the Niño4 precipitation standard deviation (Fig. 1d), still exhibits large errors in most CMIP5 models with mixed improvements for individual centres.

The multi-model mean state metrics (Figs. 1c,e,f,h,i) do not exhibit significant changes from CMIP3 to CMIP5. At the individual level, half of the centres show some improvements, mostly marked for the mean zonal wind stress at the Equator in the Pacific (Fig 1h) while the net surface heat flux in the east Pacific is almost always degraded (Fig. 1i)

Atmosphere response during ENSO

Several studies point out the central role of the atmosphere general circulation model (GCM) response during ENSO in shaping the modelled ENSO (Capotondi et al. 2006, Kim et al. 2008, Guilyardi al. 2009b, Neale et al. 2008, Watanabe et al. 2010, Lloyd et al. 2011). The Bjerknes and heat flux response are computed in Fig. 2. There is no qualitative change in the multi-model mean Bjerknes feedback (Fig. 2a) although most centres exhibit an improvement in their models. The total heat flux response in Niño3 (Fig. 2b) is improved for a few models (CNRM, MIROC5) although most see a degradation (also seen in the mean heat flux - Fig. 1i) leading to more inter-model diversity than in CMIP3. Paradoxically, a number of centres have improved shortwave and latent heat flux response (Figs. 2c-d) even though the multi-model mean value does not evolve much. Conversely a number of models have degraded shortwave heat flux response with more models having a positive feedback instead of the observed negative value of -7 Wm^{-2}/C.

While it would have been tempting to conclude from simply looking at the Niño3 anomaly standard deviations (Fig 1a) that the CMIP5 ensemble is converging on reality, examination of these physical feedbacks highlights that there is the potential for the cancellation of errors leading to such convergence. This shows the power of examining these process-based metrics.

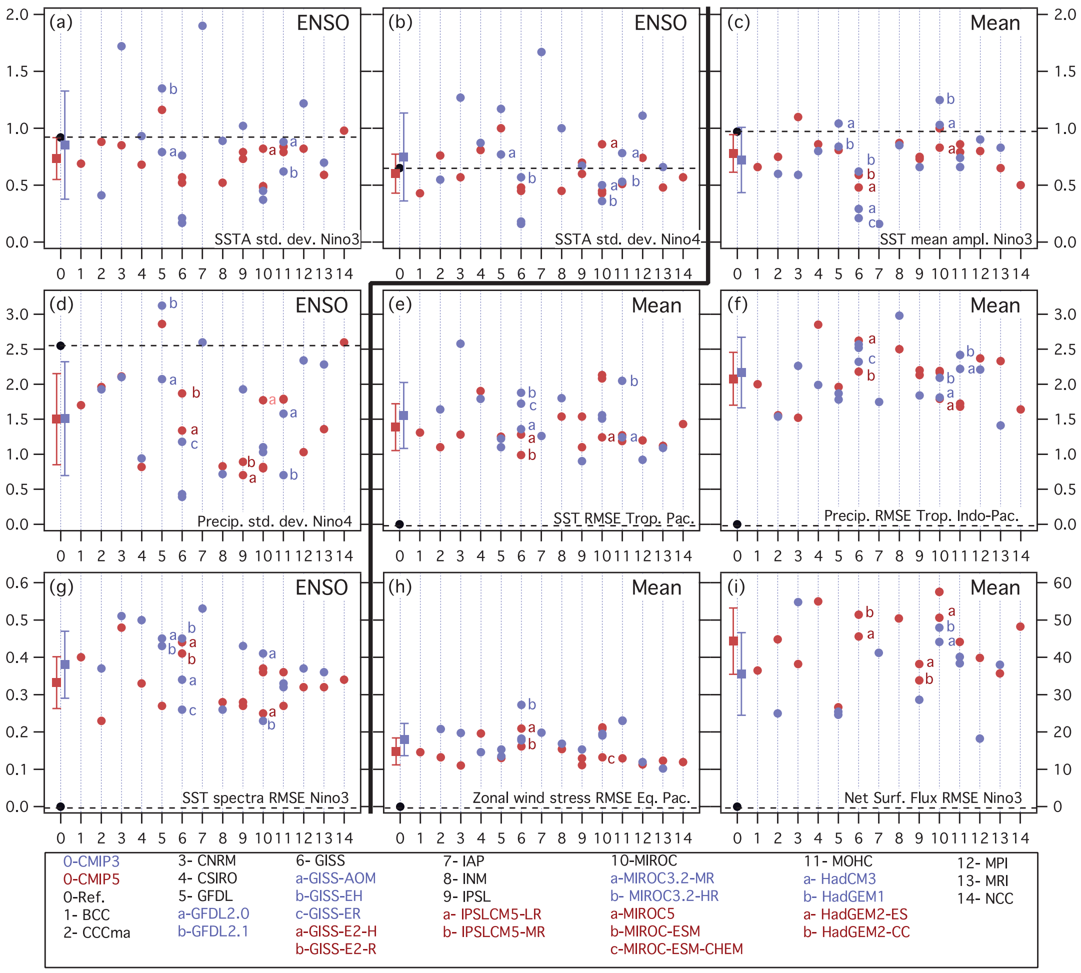

Fig. 1. ENSO and mean tropical Pacific metrics for pre-industrial control simulations - CMIP3 (blue) and CMIP5 (red). (a) and (b) SSTA std. dev. in Niño 3 and Niño 4 (°C), (c) SST annual cycle amplitude in Niño3, (°C), (d) precipitation response (std dev) in Niño4 (mm/day), (e) SST RMS error in tropical Pacific, (°C), (f) precipitation spatial RMS error over tropical Indo-Pacific, 30°N-30°S (mm/day), (g) ENSO power spectrum (Niño3) RMS error, (°C2), (h) zonal wind stress spatial RMS error over equatorial Pacific 5°N-5°S (10–3Nm–2), (i) net surface heat flux RMS error in Niño 3 (Wm–2). Reference datasets, shown as black solid circles and dashed lines: HadISST1.1 for (a), (b), (c), (e) and (g); ERA40 for (h); CMAP for (d)(f); OAFlux for (i). The CMIP3 and CMIP5 multi-model mean are shown as squares on the left of each panel with the whiskers representing the model standard deviation. Monthly atmosphere grid CMIP5-variable used: ts for (a), (b), (c), (e) and (g); tauu for ERA40 for (h); pr for (d)(f); hfls (latent), hfss (sensible), rlds (LW down), rlus, (LW up), rsds (SW down), rsus (SW up) to obtain qnet=-hfls-hfss+rlds+rsds-rlus-rsus (i). All fields were interpolated onto a common 1degree grid and then time averaged for mean fields. See metrics http://www.locean-ipsl.upmc.fr/~ENSO_metrics/index.html for details of computation.

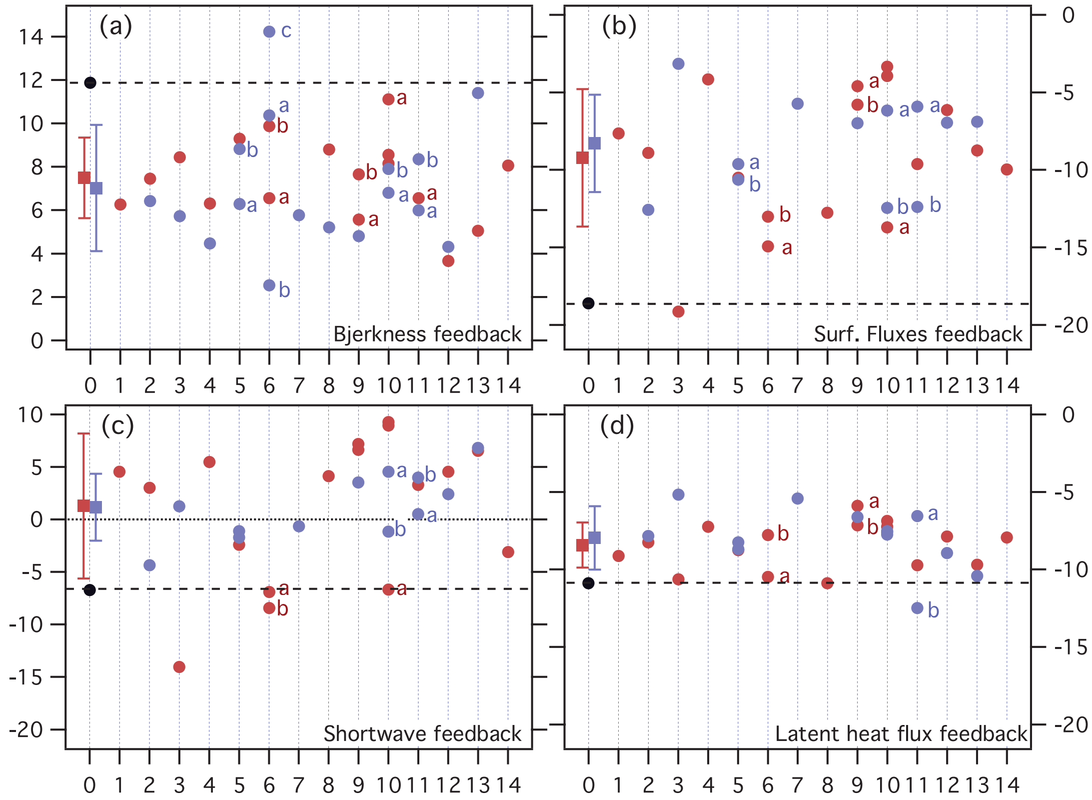

Fig. 2. Atmosphere feedbacks during ENSO for pre-industrial control simulations - CMIP3 (blue) and CMIP5 (red). (a) Bjerknes feedback, computed as the regression of Niño 4 wind stress over Niño3 SST (10−3Nm−2/C); (b) heat flux feedback, computed as the regression of total heat flux over SST in Niño3 (Wm-2/C); (c) Shortwave component of (b); (d) Latent heat flux component of (b). References: ERA40 for (a) and OAFlux for (b), (c) and (d). Monthly atmosphere grid CMIP5-variable used as described in Fig. 1. See models and centres legend in Fig. 1.

ENSO in a warmer world

Under increasing greenhouse gases, a fairly robust signal of changes in mean climate was seen in the CMIP3 models (Vecchi et al., 2006; Collins et al., 2010) and preliminary analysis of changes in mean circulation and SST in the CMIP5 models (figures not shown) indicates similar patterns.

Changes in mean climate can disrupt the balance of feedbacks in the ENSO cycle and lead to changes in the average amplitude of events. Because the balance of feedbacks is different in different models (Fig. 2), any changes in feedbacks, even if they are robust across models, can lead to different changes in basic ENSO characteristics (e.g. Philip and van Oldenborgh, 2006). Some CMIP3 CGCMs exhibited increasing ENSO variability in the future simulations, some showed a decrease and some showed no change. While the reasons for the spread in models results have been better understood in recent years, attaching likelihood to the different models and projecting future changes have not been possible.

It appears, from the preliminary analysis presented in Fig. 3, that the situation is not changed in the CMIP5 models. Six CGCMs show no significant change in Niño3 standard deviation, five show a significant increase and two show a significant decrease. Further analysis for the reasons for these changes is required. A preliminary analysis of the power spectra of Niño3 SST anomalies of events also reveals that there is no consistent picture of changes in the time scale of ENSO as greenhouse gases rise.

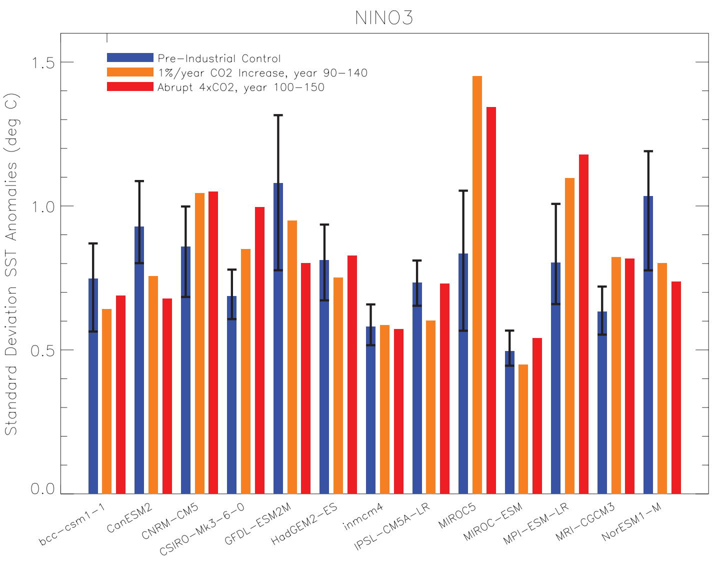

Fig. 3: Standard deviation of Niño3 SST anomalies for CMIP5 model experiments. Blue bars, pre-industrial control experiments, orange bars, years 90-140 from the 1%/year CO2 increase experiments, red bars years 50-150 from the abrupt 4xCO2. Calculations are performed for the models indicated on the x-axis. The black 'error bar' indicates the minimum and maximum of 50-year windowed standard deviation of Niño3 anomalies computed from the multi-century control experiments. Thus, when the Niño3 standard deviation in one of the CO2 runs falls below or above the error bar, the changes are deemed to be significant. If significant changes are seen in both experiments that indicates a more robust response in that model.

Conclusion and next steps

With only part of the data available, CMIP5 as a multi-model ensemble does not exhibit a quantum leap in ENSO performance or sensitivity, compared to CMIP3 as a multi-model ensemble. Looking at individual modeling centres, about half show an improvement in ENSO amplitude. The multi-model mean state does not exhibit significant changes from CMIP3 to CMIP5, although a number of individual centres saw an improvement. Very few models score better for all metrics and most have pluses and minuses. Examination of a selection of physical feedbacks highlights that there is still the potential for the cancellation of errors and that a process-based analysis is fundamental to properly assess ENSO in CGCMs. As in CMIP3, CMIP5 CGCMs exhibit a range of behaviour for ENSO variability in the future simulations, some showing an increase, others a decrease and some no change.

We also note that many of the new CGCMs are simulating much more processes than they were in CMIP3 – aerosol indirect effect, stratosphere/troposphere interactions, land ice, flowing rivers, carbon cycle, ecosystems, and forcing by emissions rather than concentrations. This makes things more challenging: there are new feedbacks to amplify biases, more uncertain model parameters to constrain and more constraints when finalizing the model set up. But this also holds promise: new avenues for improvement, better contact with observational & theoretical constraints, and new realms of ENSO impacts to be explored.

To help make further progress, a CLIVAR-sponsored workshop held in 2010 (Guilyardi et al. 2012) reviewed "new strategies for evaluating ENSO processes in climate models". Main recommendations included:

- Reduce mean state biases in CGCMs and develop pathways to understand and reduce modeled ENSO biases, including process-based analysis;
- Understand causes for El Niño and La Niña inter-event diversity, low-frequency modulation of ENSO and its impacts and how weather and climate of the mid-latitudes and other tropical regions may influence ENSO;
- Understand how ENSO may change under global warming, including quantifying and reducing uncertainty in projections;
- Continue to "bring together the different communities of experts to collectively make significant progress in the representation of ENSO in CGCMs and in the use of CGCMs in addressing open questions in ENSO science."

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References

Capotondi, A., A. Wittenberg, and S. Masina, 2006: Spatial and temporal structure of tropical Pacific interannual variability in 20th century coupled simulations. Ocean Modelling, 15, 274-298.

Collins, M., et al., 2010: The impact of global warming on the tropical Pacific Ocean and El Niño. Nature Geosci., 3 (6), 391–397, URL http://dx.doi.org/10.1038/ngeo868.

Guilyardi, E., A. Wittenberg, A. Fedorov, M. Collins, C.Z. Wang, A. Capotondi, G.J. van Oldenborgh, and T. Stockdale (2009a): Understanding El Niño in ocean-atmosphere General Circulation Models: Progress and challenges. Bull. Amer. Met. Soc., 90, 325–340

Guilyardi E., P. Braconnot, F.-F. Jin, S. T. Kim, M. Kolasinski, T. Li and I. Musat (2009b). Atmosphere feedbacks during ENSO in a coupled GCM with a modified atmospheric convection scheme. J. Clim., 22, 5698-5718

Guilyardi E. and A. Wittenberg (2010). ENSO and tropical Pacific metrics for CMIP5. IPCC Expert meeting on Assessing and Combining Multi Model Climate Projections, Boulder, USA, January 2010

Guilyardi, E., W. Cai, M. Collins, A. Fedorov, F.-F. Jin, A. Kumar, D.-Z. Sun, A. Wittenberg (2012). CLIVAR workshop summary: New strategies for evaluating ENSO processes in climate models. Bull. Amer. Met. Soc., in press now published doi:10.1175/BamS-d-11-00106.1 BAMS vol 92(check), 335-338

Kim, D., J.-S. Kug, I.-S. Kang, F.-F. Jin, and A. T. Wittenberg, 2008: Tropical Pacific impacts of convective momentum transport in the SNU coupled GCM. Climate Dyn., 31, 213-226. doi:10.1007/s00382-007-0348-4.

Lloyd, J., E. Guilyardi and H. Weller (2011), The role of atmosphere feedbacks during ENSO in the CMIP3 models, Part II: using AMIP runs to understand the heat flux feedback mechanisms, Clim. Dyn. 37, 1271-1292, DOI: 10.1007/s00382-010-0895

McPhaden, M. J.; Zebiak, S. E. & Glantz, M. H. (2006). ENSO as an Integrating Concept in Earth Science science, 314, 1739-1745

Neale, R. B., Richter, J. H., & Jochum, M. (2008). The Impact of Convection on ENSO: From a Delayed Oscillator to a Series of Events. Journal of Climate, 21(22), 5904–5924. doi:10.1175/2008JCLI2244.1

Philip, S. Y. & van Oldenborgh, G. J. (2006). Shifts in ENSO coupling processes under global warming. Geophys. Res. Letts. 33, L11704

Rayner NA, Parker DE, Horton EB, Folland CK, Alexander LV, Rowell DP, Kent EC, Kaplan A (2003) Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century. J Geophys Res (Atmos) 108:4407

Stevenson, S., Fox-Kemper, B., Jochum, M., Rajagopalan, B., & Yeager, S. G. (2010). ENSO Model Validation Using Wavelet Probability Analysis. Journal of Climate, 23(20), 5540–5547. doi:10.1175/2010JCLI3609.1

Uppala et al. (2005) The ERA-40 Re-analysis. Quart J R Met Soc 131:2961–3012

Vecchi, G. A., and A. T. Wittenberg, 2010: El Niño and our future climate: Where do we stand? Wiley Interdisciplinary Reviews: Climate Change, 1, 260-270. doi:10.1002/wcc.33

Vecchi, G. A. et al. Weakening of tropical Pacific atmospheric circulation due to anthropogenic forcing. Nature 441, 73–76 (2006).

Watanabe, M., Suzuki, T., O'ishi, R., Komuro, Y., Watanabe, S., Emori, S., Takemura, T., et al. (2010). Improved Climate Simulation by MIROC5: Mean States, Variability, and Climate Sensitivity. Journal of Climate, 23(23), 6312–6335. doi:10.1175/2010JCLI3679.1

Wittenberg, A. T. (2009), Are historical records sufficient to constrain ENSO simulations?, Geophys. Res. Lett., 36, L12702, doi:10.1029/2009GL038710.

Xie, P., and P.A. Arkin, 1997: Global precipitation: A 17-year monthly analysis based on gauge observations, satellite estimates, and numerical model outputs. Bull. Amer. Meteor. Soc., 78, 2539 - 2558.

Yu, L., and R. A. Weller, 2007: Objectively Analyzed air-sea heat Fluxes for the global oce-free oceans (1981–2005). Bull. Ameri. Meteor. Soc., 88, 527–539