Final report, DOE DE-FG02-07ER64469: Understanding annual-cycle-ENSO interactions in climate change simulations

Niklas Schneider, Axel Timmermann, University of Hawaii

This project investigated the El Nino/Southern Oscillation (ENSO), secular changes and decadal dynamics, with one emphasis on interactions between ENSO and the annual cycle as exemplified by the late winter peak in ENSO variance. The project has resulted in a total of 20 publication listed at the end, and the MS. and Ph.D. theses of Karl Stein. Furthermore, the project has contributed to the training of two postdoctoral fellows, Matthew Widlansky and Yoshinori Sasaki. A brief synopsis based on the published abstracts is presented below.

The topic of ENSO - annual cycle interaction has lead to the successful defense of Dr. Karl Stein's Masters (Stein 2008) and PhD theses (Stein 2013). He focused on fundamental ENSO dynamics and found that the annual evolution of ENSO variance results from the seasonal modulation of the ENSO growth rate, that in turn is primarily determined by the mean damping of the flow field in the eastern equatorial Pacific due to the seasonal march position of the ITCZ (Stein et al. 2010). The question of amplitude versus phase interaction was investigated for the first time in Stein et al. (2011), a paper that made the cover of Physical Review Letters and presented the first observational evidence for partial phase synchronization of the biannual ENSO and seasonal cycle. In Stein et al. (2014) we followed this investigation with a systematic exploration of ENSO characteristics, seasonal amplitude variation, 2:1 phase locking and of the contrasting hypotheses for ENSO- annual cycle interactions: nonlinear frequency locking, or linear dynamics with seasonally varying stability. Using a parametric recharge oscillator (PRO) model of ENSO, we test which of these scenarios provides a better explanation of the observed ENSO synchronization. Analytical solutions of the PRO model show that the annual modulation of the growth rate parameter results directly in ENSO's seasonal variance, amplitude modulation, and 2:1 phase synchronization to the annual cycle. The solutions are shown to be applicable to the long-term behavior of the damped model excited by stochastic noise, which produces synchronization characteristics that agree with the observations and can account for the variety of ENSO synchronization behavior in state of the art coupled general circulation models. The model also predicts spectral peaks at "combination tones" between ENSO and the annual cycle that exist in the observations and many coupled models. In contrast, the nonlinear frequency entrainment scenario predicts the existence of a spectral peak at the biennial frequency corresponding to the observed 2:1 phase synchronization. Such a peak does not exist in the observed ENSO spectrum. Hence, we conclude that the seasonal modulation of the coupled stability is responsible for the synchronization of ENSO events to the annual cycle.

The seasonal termination of large ENSO events was the subject of McGregor et al. (2012). During large El Niño events the westerly wind response to the eastern equatorial Pacific sea surface temperature anomalies (SSTAs) shifts southward during boreal winter and early spring, reaching latitudes of 5°–7°S. The resulting meridional asymmetry, along with a related seasonal weakening of wind anomalies on the equator are key elements in the termination of strong El Niño events. Using an intermediate complexity atmosphere model McGregor et al. (2012) demonstrate that these features result from an end-of-calendar-year weakening of the climatological wind speeds south of the equator associated with the seasonal intensification of the South Pacific convergence zone (SPCZ). The reduced climatological wind speeds lead to anomalous boundary layer Ekman pumping and a reduced surface momentum damping of the combined atmospheric boundary layer/lower-troposphere surface wind response to El Niño. This allows the associated zonal wind anomalies to shift south of the equator. Furthermore, McGregor et al. (2012) use a linear shallow-water ocean model and demonstrate that this southward wind shift plays a prominent role in changing zonal mean equatorial heat content and is solely responsible for establishing the meridional asymmetry of thermocline depth in the turnaround (recharge/discharge) phase of ENSO. This result calls into question the sole role of oceanic Rossby waves in the phase synchronized termination of El Niño events and suggests that the development of a realistic climatological SPCZ in December–February/March–May (DJF/MAM) is one of the key factors in the seasonal termination of strong El Niño events.

Changes in the simulated mean circulation and of intraseasonal to interannual variability induced by biologically modulated vertical absorption profiles of solar radiation were studied in Loptien et al. (2009). Using an eddy-permitting coupled physical-biological model of the tropical Pacific, three sensitivity ocean hind-cast experiments, covering the period from 1948 to 2003, are performed. In the first one, simulated chlorophyll affects the attenuation of light in the water column, while in the second experiment, the chlorophyll concentration is kept constant in time by prescribing an empirically derived spatial pattern. The third experiment uses a spatially and temporally constant value for the attenuation depth. The biotically induced differential heating is generated by increased absorption of light in the surface layers, leading to a surface warming and subsurface cooling. In general, including biophysical coupling improves the model performance in terms of temperature and ocean circulation patterns. The effect is largest in the eastern equatorial Pacific. The vertical redistribution of heat changes the near-surface ocean circulation and subsequently influences the near-surface temperature structure. Upwelling in the eastern equatorial Pacific is enhanced, the mixed layer becomes shallower, the warm bias in the eastern Pacific is reduced, and the zonal temperature gradient increases. This leads to stronger La Nina events and an associated increase in the variability of the Nino3 SSTA time series. Furthermore, the eddy kinetic energy (EKE) associated with mesoscale eddies in the eastern equatorial Pacific increases by almost 100% because of enhanced EKE production due to enhanced horizontal and vertical shear of the mean currents.

Secular changes of sea level and precipitation in the tropical Indo-Pacific were studied in Timmermann et al. (2010) and Widlansky et al. (2012). The SPCZ is the largest rain band in the Southern Hemisphere and provides most of the rainfall to southwest Pacific island nations. In spite of various modelling efforts, the response of the SPCZ to greenhouse warming remains uncertain. Using a hierarchy of climate models Widlansky et al. (2012) show that the uncertainty of SPCZ rainfall projections in present-generation climate models can be explained as a result of two competing mechanisms. Higher tropical sea surface temperatures lead to an overall increase of atmospheric moisture and rainfall whereas weaker sea surface temperature gradients dynamically shift the SPCZ northeastward and promote summer drying in areas of the southwest Pacific. On the basis of a multi-model ensemble of 76 greenhouse warming experiments and for moderate tropical warming of 1–2°C we estimate a 6% decrease of SPCZ rainfall with a multi-model uncertainty exceeding ±20%. For stronger tropical warming exceeding 3°C, a tendency for a wetter SPCZ region is identified.

Global sea level rise due to the thermal expansion of the warming oceans and freshwater input from melting glaciers and ice sheets is threatening to inundate low-lying islands and coastlines worldwide. At present the global mean sea level rises at 3.1 ± 0.7 mm yr^{-1} with an accelerating tendency. However, the magnitude of recent decadal sea level trends varies greatly spatially, attaining values of up to 10 mm yr^{-1} in some areas of the western tropical Pacific. Identifying the causes of recent regional sea level trends and understanding the patterns of future projected sea level change is of crucial importance. Using a wind-forced simplified dynamical ocean model, Timmermann et al. (2010) show that the regional features of recent decadal and multidecadal sea level trends in the tropical Indo-Pacific can be attributed to changes in the prevailing wind regimes. Furthermore, they demonstrate that within an ensemble of 10 state-of-the-art coupled general circulation models, forced by increasing atmospheric CO_2 concentrations over the next century, wind-induced redistributions of upper-ocean water play a key role in establishing the spatial characteristics of projected regional sea level rise. Wind-related changes in near-surface mass and heat convergence near the Solomon Islands, Tuvalu, Kiribati, the Cook Islands, and French Polynesia oppose - but cannot cancel - the regional signal of global mean sea level rise.

The interaction of ENSO with extra-tropical North Pacific decadal variability was studied in Di Lorenzo et al. (2010) by exploring the interaction with central Pacific Pacific warming El Nino of North Pacific Gyre Oscillation (NPGO), a climate pattern associated with decadal fluctuations in the strength of the gyre- scale circulation and linked to previously unexplained fluctuations of salinity, nutrient, and chlorophyll in the northeast Pacific (Di Lorenzo et al. 2009) and results from forcing by the North Pacific Oscillation (NPO, Chhak et al. 2009). The spatial signature of the NPGO's decadal variations is characterized by maximum sea surface temperature anomalies that extend in the central tropical Pacific and resemble the central Pacific warming (CPW) El Nino - a dominant mode of interannual variability with far-reaching effects on global climate patterns. Using an ensemble of simulations of a coupled ocean-atmosphere model Di Lorenzo et al. (2010) show that the CPW sea surface temperature anomalies drive low-frequency changes in the extra- tropical atmospheric circulation that are integrated and filtered by the ocean to form the decadal NPGO. In this new framework, tentative evidence for more frequent CPW events under greenhouse forcing scenarios is consistent with a more energetic late 20th century NPGO, implying that NPGO may play an increasingly important role in shaping Pacific climate and marine ecosystems in the 21st century.

To evaluate North Pacific decadal variability (NPDV) in past and future climate, Furtado et al. (2010) explore the two leading modes of North Pacific sea surface temperature and sea level pressure, as well as their connections to tropical variability, using multiple-ensembles of the twenty-four coupled climate models of the IPCC Fourth Assessment Report. Results indicate that the two dominant modes of ocean variability in the North Pacific, the Pacific Decadal Oscillation (PDO) and the NPGO, do not exhibit significant changes in their spatial and temporal characteristics between the 20th and 21st (SRESA1B scenario) century climates. The joint statistics between the two ocean modes and the two dominant modes of North Pacific atmospheric variability, the Aleutian Low (AL) and the NPO (see Chhak et al. 2009), are also unchanged. However, the realism of the models in capturing the dynamics of the ocean modes, including their dynamical link to the corresponding atmospheric forcing patterns and to tropical variability, is questionable. The temporal and spatial statistics of the North Pacific ocean modes exhibit significant discrepancies from observations in their 20th century climate, most visibly for the second mode, which captures a higher fraction of the total variance and significant more low-frequency power than in the observational equivalent. The dynamical coupling between the ocean and atmosphere modes evident in the observations is very strong in the models for first atmosphere/ ocean modes (AL/PDO), however, the link for the second atmosphere/ocean modes (NPO/NPGO) is not as clearly reproduced with some models showing no relationship. The teleconnection from the tropics to the extra-tropics are also problematic. In contrast with observations, the atmospheric teleconnection excited by the El Niño-Southern Oscillation (ENSO) in the models does not project strongly on the AL/PDO modes because the center of action of the AL in most models is displaced southwestward. Moreover, most models fail to show the observational connection between Central Pacific Warming (CPW)-type El Niño and NPO-variability in the North Pacific. In fact due to the southward displacement of the AL, the atmospheric teleconnections of the CPW in some models have a significant projection on, and excite, the AL/PDO mode. Overall our results suggest that characterizing and understanding NPDV in coupled climate models requires a careful consideration of the model's ENSO/CPW dynamics, its statistics, and its connection to the midlatitudes. Analyses that focus on the North Pacific variability of climate models in isolation from tropical dynamics are likely to lead to an incomplete view, and inadequate prediction, of NPDV. Moreover, the emergence of the CPW as an important tropical climate mode, and its lack of representation in the models, raises the uncertainties associated with future climate projections of North Pacific and, to a degree, of global variability.

The linkage of basin scale NPGO to boundary currents in the western North Pacific via Rossby waves is the subject of Ceballos et al. (2009). These waves are excited by the NPO, propagate the NPGO signature in the sea surface height (SSH) field from the central North Pacific into the Kuroshio–Oyashio Extension (KOE), and trigger changes in the strength of the KOE with a lag of 2–3 yr. This suggests that the NPGO index can be used to track changes in the entire northern branch of the North Pacific subtropical gyre. These results also provide a physical mechanism to explain coherent decadal climate variations and ecosystem changes between the North Pacific eastern and western boundaries.

The dynamics of decadal variations of the jet mid-latitude jets such as the Kuroshio and Gulf Stream are explored in a series of papers, that adapt the thin jet approximation to decadal time scales (Sasaki and Schneider 2011a, 2011b, Sasaki et al. 2013). In contrast to the traditional Rossby wave dynamics linearlized about a state of rest, this approach takes into account the sharp potential vorticity fronts of the western boundary current jet and focuses on changes of their location. In Sasaki and Schneider (2011a) meridional shifts of the Kuroshio Extension (KE) jet on decadal time scales are examined using a 1960–2004 hindcast simulation of an eddy-resolving ocean general circulation model for the Earth Simulator (OFES). The leading mode of the simulated KE represents the meridional shifts of the jet on decadal time scales with the largest southward shift in the early 1980s associated with the climate regime shift in 1976/77, a result confirmed with subsurface temperature observations. The meridional shifts originate east of the date line and propagate westward along the mean jet axis, a trajectory inconsistent with the traditionally used linear long Rossby waves linearized in Cartesian coordinates, although the phase speed is comparable to that in the traditional framework. The zonal scale of these westward propagation signals is about 4000 km and much larger than their meridional scale. To understand the mechanism for the westward propagation of the KE jet shifts, the authors consider the limit of a thin jet. This dynamic framework describes the temporal evolution of the location of a sharp potential vorticity front under the assumption that variations along the jet are small compared to variations normal to the jet in natural coordinates and is well suited to the strong jet and potential vorticity gradients of the KE. For scaling appropriate to the decadal adjustments in the KE, the thinjet model successfully reproduces the westward propagations and decadal shifts of the jet latitude simulated in OFES. These results give a physical basis for the prediction of decadal variability in the KE.

Using satellite altimeter observations Sasaki et al. (2013) examines interannual to decadal variability of the Kuroshio Extension (KE) jet from 1993 to 2010. The leading empirical orthogonal function (EOF) mode of sea level variability in the KE region represents the meridional shift of the KE jet, followed by its strength changes with a few month lag. This shift of the KE jet lags atmospheric fluctuations over the eastern North Pacific by about three years. Broad sea level anomalies (SLAs) emerge in the eastern North Pacific 3–4 years before the upstream KE jet shift, and propagate westward along the KE jet axis. In the course of the propagation, the meridional scale of the SLAs gradually narrows, and their amplitude increases. This westward propagation of SLAs with a speed of about 5 cm s^{-1} is attributed to the westward propagation of the meridional shift of the jet, consistent with the thin-jet theory, whose importance has been suggested by previous numerical studies. In addition, the westward-propagating signals tend to conserve their quasi-geostrophic potential vorticity anomaly, which may explain the characteristic changes of SLAs during the propagation. After the westward propagating signals of positive (negative) SLAs reach at the east coast of Japan, the upstream KE jet strengthens (weakens) associated with the strength changes of the northern and southern recirculation gyres. Interestingly, this strength change of the KE jet propagates eastward with a speed of about 6 cm s^{-1}, suggesting an importance of advection by the current.

Meridional shifts of the Gulf Stream (GS) jet on interannual to decadal timescales and the corresponding oceanic changes around the GS are investigated in Sasaki and Schneider (2011b) using a near global eddy-resolving ocean model hindcast from 1960 to 2003. The simulated variability in the shifts of the GS jet axis shows good agreement with observations, and lags atmospheric fluctuations characterized by the North Atlantic Oscillation by about 2 years. This lagged response of the GS jet to the atmospheric variations is attributed to the westward propagation of the undulation of the jet axis from 45W to 75W, which has a wavelength of about 4000 km and a displacement of 0.5. The propagation direction and phase speed of about 2.8 cm s^{-1} are consistent with the thin-jet theory. The shifts of the jet axis in the downstream region are likely induced by wind fluctuations through Ekman convergence over the central North Atlantic.

Associated with the northward (southward) shift of the jet axis, sea surface temperature is warming (cooling) around and north of the jet, and the former warming has a deep and meridionally narrow subsurface structure, consistent with the northward shift of the jet. The meridional shifts of the jet accompany coherent meridional shifts of energetic eddy activity regions around the GS. Our numerical results suggest that the GS jet brings the atmospheric signals from the central to the western North Atlantic, and the resultant meridional shift of the jet induces the notable oceanic changes around the GS.

Finally, the linkages of North Pacific decadal changes back to the tropical Pacific are explored in Sasaki et al. (2010). The propagation of density-compensated (warm/salty or cool/fresh) spiciness anomalies in the North Pacific thermocline is investigated using Argo profiles for the period 2001–2008. A cool/fresh spiciness anomaly on density surfaces between 25 and 25.5 kg m^{-3} isopycnals appears in the eastern subtropical North Pacific at 120°W–150°W in 2003–2004 with a salinity anomaly of about –0.15 PSS-78. This spiciness anomaly migrates southwestward, and arrives in the western tropical North Pacific at 145°E–175°W in 2008 with the salinity anomaly decreasing to about –0.043 PSS-78. Two warm/salty anomalies are observed to propagate along the same path from 2003 to 2005, and after 2005. The propagation path and speed of the anomalies are in good agreement with advection by the mean geostrophic current. In the course of propagation, the anomalies are diffused and are subject to high frequency injection of spiciness anomalies, especially in the eastern subtropical North Pacific.

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