Global impacts:
- **weather & climate**, extremes, natural disasters
- **ecosystems**, fisheries, agriculture, forests
- **economies**: commerce, transportation, energy, water, food, health

How vulnerable are we to ENSO?
- sources & limits of seasonal-to-decadal **predictability**
- **natural vs. anthropogenic risks**
- changes in **dynamics** vs. **impacts**
- short, gappy, nonstationary observing system → **models crucial**
- coupling & scale interactions → **key test** for models
GFDL: Strongly positioned in the ENSO community

**ENSO simulations among the best in the world**

- **realistic** ENSO behavior: patterns, spectra, mechanisms, teleconnections
- **stable** multi-millennial control runs, large ensembles
- **diverse** model tools, complementary assimilation & forecast systems

Wittenberg et al. (JC 2014; JAMES 2018); Vecchi et al. (JC 2014); Wittenberg (CV 2015); Choi et al. (JC 2015); Delworth et al. (JC 2015); Krishnamurthy et al. (JC 2015, 2016; CD 2019); Griffies et al. (JC 2015); Jia et al. (JC 2015); Yang et al. (JC 2015; CD 2018); Ward et al. (ERL 2016); Zhang et al. (JC 2016); Ray et al. (JC 2018ab); Zhao et al. (JAMES 2018a); He et al. (JC 2018); Park et al. (GRL 2018); Held et al. (JAMES 2020); Johnson et al. (JC 2020); Delworth et al. (JAMES subm); Dunne et al. (in prep)

**Groundbreaking ENSO research & collaborations**

- **Diversity**, sensitivities & trends, mechanisms
- **Predictability**, forecasts, observing system design
- **Impacts** on hydroclimate, storms, extremes, ecosystems
- **Community metrics**, emergent constraints, model hierarchy

60+ peer-reviewed papers related to ENSO during 2014-19, with 2300+ citations (Google Scholar, Sept. 2019)

NOAA & U.S. collaborations: ESRL, AOML, PMEL, NCEP, NDBC, CPO; U.S. CLIVAR Working Group on ENSO Diversity, International: CLIVAR (Research Focus on ENSO; Working Group on ENSO Metrics; Pacific Region Panel); CMIP; IPCC; NMME; TPOS2020.

Collaborative studies: Lee et al. (GRL 2014, 2018; ERL 2016); Capotondi et al. (BAMS 2015; CV 2015); Erb et al. (JC 2015); Cravatte et al. (TPOS 2016); Guilyardi et al. (BAMS 2016); Zhang et al. (GRL 2016); Atwood et al. (CD 2017); Chen et al. (JC 2017); Graham et al. (CD 2014, 2017; JC 2015); L'Heureux et al. (BAMS 2017; WF 2019); Naiman et al. (JC 2017); Stuecker et al. (GRL 2017); Predybaylo et al. (JSRA 2017); Newman et al. (BAMS 2018); Ding et al. (JC 2018; GR 2019); Timmermann et al. (Nature 2018); Chiodi et al. (GBC 2019); Kessler et al. (TPOS 2019); Vecchi et al. (CD 2019); Capotondi et al. (AGU 2020); Fedorov et al. (AGU 2020); Guilyardi et al. (AGU 2020); Predybaylo et al. (SA subm); Santidrian et al. (CC subm); Lee et al. (in prep); McGregor et al. (in prep); Power et al. (in prep); Stevenson et al. (in prep)
ENSO improvements with increasing resolution

Vecchi et al. (JC 2014; CD 2019); Jia et al. (JC 2015); Yang et al. (JC 2015); Wittenberg et al. (JAMES 2018); Ray et al. (JC 2018ab)
Improved ENSO patterns & spectra in CM4

Better resolution & comprehensiveness
→ New avenues for research & applications

Zhao et al. (JAMES 2018a)
Held et al. (JAMES, in press)
ENSO diversity in observations

ENSO flavors have different dynamics & impacts

ENSO diversity in observations & models

ENSO flavors have different dynamics & impacts


Sources, impacts, predictability: Wittenberg et al. (JC 2014); Graham et al. (CD 2017); Chen et al. (JC 2017); Atwood et al. (CD 2017); L’Heureux et al. (BAMS 2017); Yang et al. (CD 2018); Timmermann et al. (Nature 2018); Johnson et al. (GRL 2019); Santidrian et al. (CC subm)
Improved seasonal synchronization of ENSO

**Observed** events (especially strong ones) tend to peak during Oct-Dec.

**GFDL-FLOR** (like many models) didn’t capture this.

Correct climatological SST & wind stress using **flux adjustments (FA)** → ENSO **synchronizes** to end of calendar year.

FA corrects east Pacific seasonality of **dT/dy** and **ITCZ latitude**.

Boosts SST→wind coupling during the key Jun-Nov season of ENSO growth.

*Wittenberg et al. (in prep)*
ENSO diversity & seasonality affect remote impacts

Key flavors of observed ENSO evolution

ENSO events show diverse temporal behavior in boreal spring:
- persisting,
- terminating early,
- resurging,
- or transitioning.

This significantly affects ENSO impacts,
- e.g. on U.S. tornado outbreak frequency
- & California rainfall.

Lee et al. (GRL 2014, 2018; ERL 2016)
Krishnamurthy et al. (JC 2015)
Historical changes in ENSO & mean eq. Pacific SST

Newman, Wittenberg, et al. (BAMS 2017)
Historical changes in ENSO & mean eq. Pacific SST

Mean SST change marginally detectable. ENSO change, less so.

Newman, Wittenberg, et al. (BAMS 2017)
ENSO responses to increasing CO₂

CM2.1 simulations show interplay of intrinsic ENSO modulation, multidecadal climate, nonlinear sensitivity, and regional responses to increasing CO₂.

Further work:
- Knutson et al. (BAMS 2014)
- Cai et al. (NCC 2014)
- Delworth et al. (JC 2015)
- Choi et al. (JC 2015)
- Kam et al. (BAMS 2016)
- Chen et al. (JC 2017)
- Graham et al. (CD 2017)
- Atwood et al. (CD 2017)
- Timmermann et al. (Nature 2018)
- Fedorov et al. (AGU 2020)
- Stevenson et al. (in prep)
CMIP5 projections (PI, 1900-99, 2000-99)

No CMIP5-model consensus on future ENSO SSTA amplitude. But they do suggest changes in ENSO’s dynamics & evolution.

Chen et al. (JC 2017)
Emergent constraints for future ENSO extremes

Models project a wide range of changes in **El Niño rainfall extremes**: some **strongly increase**, others **decrease**.

"**Increasers**" start with common biases: **cooler & drier** cold tongue, **weaker** ENSO, and **weaker heat flux damping** of SST changes.  
→ More room to amplify ENSO extremes.

Increasers also project **more future warming, wetting, and ENSO SSTA amplification** in the cold tongue.

Can use these **emergent constraints** to leverage model diversity and inform future projections.

Stevenson et al. (in prep)
Community metrics for ENSO simulations

CLIVAR Research Focus on ENSO – Guilyardi et al. (AGU 2020); Planton et al. (in prep)

- Provide multi-model context
- Compare to other models & metrics
- Discover connections among metrics, find emergent constraints
- Inter-model correlations among metrics

Example: El Niño life cycle

Warm events: NINO3 SSTa (°C) detrended, smoothed with 5mo triangle
1961–2016 composite, Dec(0) NINO3 SSTA > 0.75°C

Inter-model correlations
**ENSO forecasts using model-analogs**

*Existing long model control runs* are like “libraries” of ENSO behavior. Find analogs of obs SST & SSH → trace how those states evolved in control runs.

→ Like a forecast with no initialization shock.

At 6-month leads in the tropics, analogs from the NMME control runs beat the same models’ initialized forecasts!

Suggests that even models without assimilation (e.g. CMIP5) could offer useful forecast guidance.

Also permits rapid assessment of secular variations in predictability.

*Ding et al. (JC 2018; GRL 2019)*
Future plans and challenges

1. Better understand ENSO & improve models
   a. **Background climate** is key (flux adjustments, heat/momentum budgets)
   b. Community metrics & obs **constraints** (TPOS2020, LES, reanalyses, paleo)
   c. Enhance model **resolution & physics**
      - clouds & convection, surface winds & fluxes, ocean mixing (TIWs), diurnal cycle

2. Improve predictions & projections
   a. Clarify ENSO connections to **extremes & regional** impacts
   b. Understand sources & limits of **predictability** (model analogs)
   c. **Emergent constraints** to improve future projections
1. ENSO understanding & predictions are **critical to NOAA’s mission**.

2. GFDL’s ENSO simulations, forecasts, and projections are **among the world’s best**. They are widely used, and improving.

3. GFDL is rapidly **advancing community understanding** of ENSO’s diversity, dynamics, sensitivities, impacts, and predictability.


Choi, K.-Y., et al., 2015: Nonlinear zonal wind response to ENSO in the CMIP5 models: Roles of the zonal and meridional shift of the ITZC/SPCZ and the simulated climatological precipitation. J. Climate, 28, 8556-8573. doi: 10.1175/JCLI-D-15-0211.1


McGregor, H., et al.: Orbital forcing of increasing ENSO variability over the past 6,000 years. In prep.


Yang, X., et al., 2015: Seasonal predictability of extratropical storm tracks in GFDL’s high-resolution climate prediction model. *J. Climate*, **28**, 3592-3611. doi:10.1175/JCLI-D-14-00517.1


