PHYSICAL SCIENCES LABORATORY

Physical Sciences Laboratory (PSL) Publication Report

October through December 2025

19 articles, 0 reports, 0 datasets

A list of PSL-affiliated articles, datasets, and reports with abstracts from FY26 Q1. Listed alphabetically by lead author. PSL-affiliated authors at time of publication in **bold.**

October 2025

ARTICLES

Bianco, L., R. Mendeke, J. Lindblom, **I. Djalalova**, D. D. Turner and **J. M. Wilczak** (2025). Evaluating the ability of the operational High Resolution Rapid Refresh model version 3 (HRRRv3) and version 4 (HRRRv4) to forecast wind ramp events in the US Great Plains. *Wind Energ. Sci.*, 10, 2117–2136, https://doi.org/10.5194/wes-10-2117-2025.

> Incorporating more renewable energy into the electric grid is an important part of the strategy to expand our energy portfolio. To make the incorporation of renewable energy into the grid more efficient and reliable, numerical weather prediction models need to be able to predict the intrinsic nature of weather-dependent renewable energy resources. This allows grid operators to accurately plan the amount of energy they will need from each source (e.g., wind, solar, fossil fuel). For this reason, wind ramp events (rapid changes in wind speed over short periods of time) are important to forecast accurately. This is because one of their consequences is that wind energy could quickly be available in abundance or temporarily cease to exist. In this study, the ability of the operational High Resolution Rapid Refresh numerical weather prediction model to forecast wind ramp events is assessed in its two most recent versions: version 3 (HRRRv3, operational from August 2018 to December 2020) and version 4 (HRRRv4, operational from December 2020 onward). The datasets used in this analysis were collected in the United States Great Plains, an area with a large amount of installed electricity generation from wind. The results are investigated from both annual and seasonal perspectives and show that the HRRRv4 is more accurate at forecasting wind ramp events compared to HRRRv3. Specifically, the HRRRv4 shows an increased correlation coefficient and reduced root mean square error relative to the change in wind power capacity factor found in the observations and in the skill of forecasting both up and down wind ramp events, with a marked increase in the HRRRv4's skill at detecting up ramps during the summer (the HRRRv4 is nearly 50 % more skillful than the HRRRv3). This demonstrates that the HRRR's continuing evolution will better support the integration of wind energy into the electric grid.

Bytheway, J. L., D. R. Stovern, S. Trojniak, **K. M. Mahoney,** J. Correia and **B. J. Moore** (2025). Analysis of 3 years of summertime extreme precipitation forecasts from the High Resolution Ensemble Forecast System. *Wea. Forecasting*, 40, 2111–2136, https://doi.org/10.1175/WAF-D-24-0059.1.

> The High-Resolution Ensemble Forecast (HREF) system is the first operational convection-allowing ensemble in the United States. Its membership consists of five deterministic convection-allowing models, several of which are used in operational forecasting, plus five time-lagged forecasts. HREF forecasts of summertime (JJA) extreme precipitation, defined as exceeding average recurrence interval (ARI) thresholds at 2, 10, and 50 years at 1-, 6-, and 24-h accumulation periods, are evaluated over 3 years (2021–23) with a consistent model configuration. This study evaluates the representation of precipitation extremes by the ensemble, ensemble forecast performance, and the contribution of the individual members to forecasts of extreme precipitation both CONUS-wide as well as over the six different regions. Both observed and predicted ARI exceedances were found to most frequently occur over the western U.S. Forecasts of 6- and 24-h accumulations were found to be reliable for forecast probability < 30% within a 25-km radius of an observed ARI exceedance. Results for forecast probability > 50% were often noisy due to the small sample size of highly predictable extreme events. Forecast skill from both the ensemble and its individual members generally increased with increasing accumulation period and decreased with increasing ARI threshold. Time-lagged members were less likely to contribute to forecasts of extreme precipitation, having lower probability of detection and success ratio than the nonlagged members, though the lag–High-Resolution Rapid Refresh (HRRR) was often an exception. These results provide important, and heretofore lacking, contextual information to forecasters using the HREF and its individual members.

Gichamo, T. Z., **C. Draper** and M. Barlage (2025). Improving NOAA's Global NWP Snow Data Assimilation by Updating to an Ensemble Kalman Filter. *Journal of Hydrology*, 660, Part A, 133301, https://doi.org/10.1016/j.jhydrol.2025.133301.

> In an earlier study, we implemented an Optimal Interpolation (OI) for snow data assimilation (DA) in NOAA's NWP system, the Global Forecast System (GFS). This snow depth OI, which is commonly used in NWP, significantly improved snowpack fields, resulting in improved short-range forecasts of near-surface temperature. Within the hydrology community, the Ensemble Kalman Filter (EnKF) is generally favored over simpler methods such as the OI, due largely to its more realistic representation of model errors. Here, we then compare the OI and EnKF assimilation of station snow depth, confirming that the EnKF significantly outperforms the OI. Compared to independent station snow depth observations, the Unbiased Root Mean Square Error (ubRMSE) of 210 mm for the Open Loop (OL) was reduced to 186 mm by the OI and to 161 mm by the EnKF; and the bias were reduced from 65 mm to 29 mm and −7 mm by the OI and the EnKF, respectively. The Normalized Information Contribution (NIC) in terms of RMSE from OI DA was close to 17 % compared to 33 % from EnKF. Snow covered area estimates were also improved by both methods, compared to the Interactive Multisensor Snow and Ice Mapping System (IMS) snow cover data. Model snow depth errors vary considerably in space and time, and investigation of these errors shows that the superior performance of the EnKF is consistent with its ensemble-based model error estimates better capturing this variability. These results suggest NOAA's GFS could benefit from adopting an EnKF snow DA.

Goldberger, L. A., M. Levin, C. Harris, A. Geiss, **M. D. Shupe** and D. Zhang (2025). Classifying thermodynamic cloud phase using machine learning models. *Atmos. Meas. Tech.*, 18, 5393–5414, https://doi.org/10.5194/amt-18-5393-2025.

> Vertically resolved thermodynamic cloud-phase classifications are essential for studies of atmospheric cloud and precipitation processes. The Department of Energy (DOE) Atmospheric Radiation Measurement (ARM) Thermodynamic Cloud Phase (THERMOCLDPHASE) value-added product (VAP) uses a multi-sensor approach to classify the thermodynamic cloud phase by combining lidar backscatter and depolarization, radar reflectivity, Doppler velocity, spectral width, microwave-radiometer-derived liquid water path, and radiosonde temperature measurements. The measured pixels are classified as ice, snow, mixed phase, liquid (cloud water), drizzle, rain, and liq_driz (liquid+drizzle). We use this product as the ground truth to train three machine learning (ML) models to predict the thermodynamic cloud phase from multi-sensor remote sensing measurements taken at the ARM North Slope of Alaska (NSA) observatory: a random forest (RF), a multi-layer perceptron (MLP), and a convolutional neural network (CNN) with a U-Net architecture. Evaluations against the outputs of the THERMOCLDPHASE VAP with 1 year of data show that the CNN outperforms the other two models, achieving the highest test accuracy, F1 score, and mean intersection over union (IOU). Analysis of ML confidence scores shows that ice, rain, and snow have higher confidence scores, followed by liquid, while mixed, drizzle, and liq_driz have lower scores. Feature importance analysis reveals that the mean Doppler velocity and vertically resolved temperature are the most influential data streams for ML thermodynamic cloud-phase predictions. Lidar measurements exhibit lower feature importance due to rapid signal attenuation caused by the frequent presence of persistent low-level clouds at the NSA site. The ML models' generalization capacity is further evaluated by applying them at another Arctic ARM site in Norway using data taken during the ARM Cold-Air Outbreaks in the Marine Boundary Layer Experiment (COMBLE) field campaign. The models demonstrated similar performance to that observed at the NSA site. Finally, we evaluate the ML models' response to simulated instrument outages and signal degradation and show that a CNN U-Net model trained with input channel dropouts performs better when input fields are missing.

Lorenzo-Sanchez, P., **M. Newman**, **J. Albers**, A. C. Subramanian and A. Navarra (2025). Koopman Theory for Enhanced Pacific SST forecasting. *Artif. Intell. Earth Syst.*, 4, e240088, https://doi.org/10.1175/AIES-D-24-0088.1.

El Niño–Southern Oscillation (ENSO) is a complex phenomenon that significantly impacts global weather patterns and ecosystems. Improving its prediction is therefore of a high societal value. However, general circulation models (GCMs) present severe biases when predicting ENSO, and their skill remains comparable to that of vastly simpler empirical models such as linear inverse models (LIMs). LIMs, however, rely on linear dynamics, and they have inherent limitations in capturing the behavior of nonlinear phenomena. In this context, Koopman operator theory has emerged as a powerful mathematical framework, offering a novel perspective for analyzing complex nonlinear systems. Unlike LIMs, Koopman operators enable linear representations of nonlinear dynamics in infinite-dimensional function spaces, allowing for richer dynamical insights. While previous studies have demonstrated the potential of Koopman methods for ENSO forecasting, a fundamental question remains: How much data are actually needed to obtain robust Koopman operator estimates? In this study, this issue is addressed by performing a sensitivity analysis on the reliability of Koopman-based forecasts as a function of data length. Using 2000 years of tropical SST preindustrial Community Earth System Model, version 2 (CESM2), data, this study assesses the skill of the Niño-3.4 forecasts within the nonlinear Koopman framework and compares it to the benchmark set by LIMs. Our findings reveal nuances in the robustness of Koopman operator estimates, particularly when using shorter training periods. However, a notable breakthrough emerges: the higher skill of the Niño-3.4 Koopman ensemble forecasts (KEFs), which showcase consistent improvements over linear models, along with improved representation of western Pacific variability and more reliable forecasts of extreme El Niño and La Niña events.

Marsico, D. H. , S. Du and S. N. Stechmann (2025). Can second-order numerical accuracy be achieved for moist atmospheric dynamics with non-smoothness at cloud edge? *Journal of Advances in Modeling Earth Systems*, 17, e2025MS005293, https://doi.org/10.1029/2025MS005293.

Non-smoothness arises at cloud edge because, in moist thermodynamics, the thermodynamic properties of the atmosphere are different inside a cloud versus in clear air. In particular, inside a cloud, the vapor pressure of water is constrained by the saturation vapor pressure, which acts as a threshold. Due to this threshold, while the water vapor mixing ratio may vary continuously across cloud edge, its derivatives are not necessarily continuous at cloud edge. Similarly, non-smoothness also arises for buoyancy and other variables. Consequently, this non-smoothness in buoyancy and other variables can cause a degraded accuracy in computational simulations. Here we consider special treatment of numerical methods for the interface that arises from phase changes and cloud edges, in order to enhance the accuracy and potentially achieve second-order accuracy. Numerical solutions are computed for the moist non-precipitating Boussinesq equations as an idealized cloud-resolving model with phase changes of water, that is, with cloud formation. Convergence tests, both spatial and temporal, are conducted to measure the numerical error as the grid spacing and time step are refined. While approximately second-order accuracy is seen in root-mean-square (L^2) error, the accuracy is degraded in the maximum (L^∞) error. Discussion is also included on theoretical issues and potential implications for numerical simulations.

Quin, H., M. Pritchard, C. R. Terai, J. Bacmeister, P. Bogenschutz and **G. N. Kiladis** (2025). Remote influence of Andean convection on Amazonian rainfall and its mechanisms. *Journal of Geophysical Research: Atmospheres*, 130, e2025JD043465, https://doi.org/10.1029/2025JD043465.

> Models from Coupled Model Intercomparison Project Phase 6 produce too much precipitation over the Andes but too little over the Amazon or the Wet Andes-Dry Amazon (WADA) bias pattern. Unlike the conventional view that convection parameterization and land model deficiencies can contribute to Amazonian rainfall biases, we approach this long-standing biased model behavior through the lens of Andean convection. Using Community Earth System Model v1.1 and focusing on the wet season, our mechanism-denial experiments demonstrate that Andean convection notably reduces precipitation over the Amazon during austral summer. The Andean forced Amazonian response operates on weather timescale. The reduction of Amazonian rainfall is detectable within a few hours after initial Andean forcing. The precipitation response is primarily driven by variations in the moisture budget and is moderated by changes in convective available potential energy over the Amazon. Changes in the total advection of moisture over the Amazon are dominated by the vertical advection term and can be attributed to discrepancies in the dynamic omega field. In the experiments, the Andean east flank region is scrutinized where the vertical velocity and moisture fields play an intermediary role for the Andean driven WADA connection. The Andean forcing induces descending anomalies on the Andean east flank. The disturbances of wind and geopotential fields over the Andean east flank propagate eastward via Kelvin waves. Over the Amazon, descending anomalies and advective drying lead to reduction of mid-to-high level cloud, increase of shortwave cloud forcing and surface net radiation, and enhancement of themodynamic stability and rainfall reduction.

Schwat, E., D. Hogan, K. T. Paw U, **C. J. Cox**, **B. J. Butterworth**, E. Gutmann, J. A. Vano and J. D. Lundquist (2025). Estimating Snow Sublimation in Complex Terrain: A Season of Intensive Field Measurements and the Role of Vertical Water Vapor Flux Divergence. *Journal of Geophysical Research: Atmospheres*, 26, 1455–1473, https://doi.org/10.1175/JHM-D-25-0022.1.

> Understanding the role of snow sublimation in the alpine water balance is critical to predicting future water resource availability. During winter 2022–23, the Sublimation of Snow campaign in Colorado's East River watershed used 12 eddy covariance (EC) instruments (2–20-m height) to measure sublimation and micrometeorology on the valley floor. ECs measured 33–42 mm of snow water equivalent sublimated (8%–10% of seasonal peak snow accumulation). Midwinter sublimation was driven by blowing snow and springtime sublimation by positive net radiation. During blowing snow, EC water vapor fluxes increased with height between 3 and 10 m, on average by 26% and by up to 200% during individual events (positive vertical turbulent flux divergence). During nonblowing snow conditions, fluxes decreased with height between 3 and 20 m, on average by 36% (negative vertical turbulent flux divergence). Estimates of transport terms in a water vapor conservation equation suggest that positive divergence arose from blowing snow sublimation and negative divergence arose from vertical water vapor advection, although horizontal advection remains unquantified, limiting our conclusions. We found that keeping one instrument functional over the entire winter is more important than having instruments at multiple heights. Seasonal uncertainty in measured total sublimation due to instrument height is estimated at ±12% due to blowing snow sublimation and water vapor advection; however, for shorter deployments, this uncertainty may be larger. The optimal instrument height for estimating total sublimation, 10 m at our site, is likely to vary by location, and further work is needed to understand the role of advection.

Xing, C., S. Stevenson, E. Di Lorenzo, **M. Newman**, **A. Capotondi**, J. Fasullo and N. Maher (2025). Apparent Changes in Pacific Decadal Variability Caused by Anthropogenically-Induced Mean State Modulations. *Geophys. Res. Lett.*, 52, e2025GL116499, https://doi.org/10.1029/2025GL116499.

> Pacific decadal variability (PDV), reflected in low-frequency Pacific sea surface temperature (SST) changes, impacts global climate. Disentangling anthropogenic effects upon PDV is challenging because PDV and anthropogenic forcing vary on similar time scales. Using single-forcing climate model large ensembles, we find that anthropogenic forcing drives a spatially varying pattern of mean-state change in Pacific SST that projects onto PDV patterns, principally the Pacific Decadal Oscillation (PDO) and the North Pacific Gyre Oscillation (NPGO). When the trend is removed by subtracting the ensemble mean, there is no forced change of either PDV mode. However, analysis of individual ensemble members, where the mean-state trend cannot be cleanly removed, yields apparent anthropogenic changes in PDO and NPGO decadal variability. This suggests that observed PDV responses to anthropogenic forcing may be erroneously convolved with the background trend pattern. Therefore, correctly determining the mean-state trend is a necessary precursor for identifying possible forced changes to PDV.

November 2025

ARTICLES

Breeden, M. L., **A. Hoell**, **R. P. Worsnop, J. R. Albers, M. T. Hobbins, R. M. Robinson** and D. J. Vimont (2025). Seasonal Predictability of Vapor Pressure Deficit in the western United States. *Weather Clim. Dynam.*, 6, 1443–1459, https://doi.org/10.5194/wcd-6-1443-2025.

> Saturation vapor pressure deficit (VPD), a measure of the difference between how much moisture the atmosphere can hold versus how much is present, is highly correlated with the annual mean area burned by wildland fires in the western United States. The present analysis uses linear inverse models (LIMs) to forecast seasonal VPD and decompose skill into contributions from a nonlinear trend, coupled sea surface temperature (SST)-VPD variability, and VPD-only variability. Subregions of the western US are considered using Geographic Area Coordination Centers which have different times of year and lead times for which VPD forecast skill is greatest. However, the sources of skill are similar among the subregions. In LIM forecasts, particularly those made for summer and early fall, the trend contributes to VPD skill up to 18 months in advance, with a secondary contribution from internal VPD variability at lead times of one to two months. Positive SST and VPD anomalies and negative soil moisture anomalies are associated with the positive sign of the trend time series, which has been observed without interruption since the late 1990s. Coupled SST-VPD variability contributes to VPD skill mainly for forecasts verifying between December to May for lead times up to 12 months in some subregions. Forecasts that are especially skillful and display high confidence, seasonal forecasts of opportunity (SFOs), are associated with SSTs that produce high VPD skill over California, the Southwest, and Texas, while internal VPD anomalies contribute to skill over the Great Basin and western Northern Plains. SFOs are initialized during periods of El Niño-Southern Oscillation development, with La Niña SSTs associated with positive western US VPD anomalies and consequently, enhanced wildland fire risk.

Butterworth, B. J., B. Else, K. A. Brown, C. J. Mundy, W. J. Williams, L. M. Rotermund and G. de Boer (2025). Annual carbon dioxide flux over seasonal sea ice in the Canadian Arctic. *The Cryosphere*, 19, 5317–5335, https://doi.org/10.5194/tc-19-5317-2025.

> Continuous measurements of carbon dioxide (CO_2) flux were collected from a 10 m eddy covariance tower in a coastal-marine environment in the Canadian Arctic Archipelago over the course of a 17-month period. The extended length of data collection resulted in a unique dataset that includes measurements from two spring melt and summer seasons and one autumn freeze-up. These field observations were used to verify findings from previous theoretical and laboratory experiments investigating air-sea gas exchange in connection with sea ice. The results corroborated previous findings showing that thick ice cover under winter conditions acts as a barrier to gas exchange. In the spring, CO_2 fluxes were downward (uptake) in both the presence of melt ponds and during ice break-up. However, diurnal cycles were present throughout the early spring melt period, corresponding to the opposing influences of freezing and melting at the ice surface. Fluxes measured during melt periods confirmed previous laboratory tank measurements that showed a gas transfer coefficient of melting ice of $0.4\,\mathrm{mol\,m^{-2}\,d^{-1}\,atm^{-1}}$. Open water CO_2 fluxes showed outgassing in early summer and uptake in mid-to-late summer, tied closely to trends in surface water temperature and its effect on the partial pressure of CO_2 in the water. The autumn period of the field campaign represents the first eddy covariance CO_2 fluxes measured over naturally forming sea ice. Our measurements showed mean upward fluxes (outgassing) of $1.1 \pm 1.5\,\mathrm{mmol\,m^{-2}\,d^{-1}}$ associated with the freezing of ice – the same order of magnitude found by previous laboratory tank experiments. However, peak flux periods during ice formation had measured fluxes that were a factor of 3 higher than the tank experiments, suggesting the importance of natural conditions (e.g., wind) on air-ice gas exchange. Conducting an Arctic-wide extrapolation we estimate CO2 outgassing from the freezing period to be a counterbalance equivalent to 5 to 15 % of the magnitude of the estimated Arctic CO_2 sink. Overall, there was no evidence of dramatically enhanced gas exchange in marginal ice conditions as proposed by previous studies. Although the different seasons showed active CO_2 exchange, there was a balance between upward and downward fluxes at this specific location, resulting in a small net CO_2uptake over the annual cycle of $-0.3\,\mathrm{g\,C\,m^{-2}}$.

Li, J., A. J. Miller, **D. J. Amaya,** W. Wang, P. Li, Y. Gu and P. Bai (2025). Vertical structure of chlorophyll-a during marine heatwaves in the California Current Ecosystem. *Commun Earth Environ*, 6, 938, https://doi.org/10.1038/s43247-025-02835-8.

In the past decades, the California Current Ecosystem has experienced intense marine heatwaves, which have induced significant disruptions to local phytoplankton communities. Here, using 30-year cruise observations, we identify a previously undocumented vertical structure in chlorophyll-a concentration response to marine heatwaves, characterized by reductions in the surface layer coupled with increases in the subsurface. By integrating observations and coupled physical-biogeochemical model products, we demonstrate that declines of surface chlorophyll-a are primarily attributed to suppressed nutrient upwelled to the upper ocean. Although surface irradiance increased modestly (+3.5%), light availability in the subsurface layer improved substantially (+21.7%) due to reduced phytoplankton shading at the surface. Concurrent with enhanced lateral nutrient transport, phytoplankton growth at depth was promoted during heatwave events. This study highlights the pivotal role of subsurface phytoplankton dynamics in shaping the vertical chlorophyll-a concentration structure and its variability under extreme events.

Towler, E., J. M. Done, M. Ge and E. Gilleland (2025). Seasonal forecasting of precipitation-relevant weather types over the United States. *Wea. Forecasting*, 40, 2239–2253, https://doi.org/10.1175/WAF-D-24-0230.1.

This paper evaluates seasonal forecasts of weather types (WTs), i.e., recurring large-scale atmospheric patterns, which have been developed using a clustering method using large-scale predictors to represent precipitation variability across the United States. Forecast quality is assessed using two seasonal hindcast products: from the operational weather community, hindcasts from the European Centre for Medium-Range Weather Forecasts (ECMWF), as well as hindcasts from the Community Earth System Model, version 2 (CESM2), a community resource developed by the NSF National Center for Atmospheric Research [...] WTs are described in terms of their associated precipitation anomalies and examined in light of their relationship with established climate teleconnections. The spatial precipitation patterns associated with each WT are less well captured in the forecasting systems than the large-scale variables from which the WTs are derived. The WT patterns themselves are well represented in both seasonal forecasting systems, though, on average, ECMWF is slightly closer to observations. Forecasted WT frequency results show that both prediction systems have similar skill, with most differences depending on season and WT. Winter WT frequencies are generally more predictable than summer. Both forecast systems capture well the frequency rank order but underestimate the interannual frequency spread, which could be partially due to ensemble averaging. Analysis shows that forecasting of climate teleconnection indices alone would not be sufficient to represent the precipitation variability associated with the WTs. Comparable results from two initialized Earth system prediction models that originate from different sides of the weather–climate and operations–research spectrum are encouraging and contribute to WT forecasting and multimodel initialized prediction efforts.

Wendisch, M., B. Kirbus, D. Ori, **M. D. Shupe**, et al. (2025). Observed and modeled Arctic airmass transformations during warm air intrusions and cold air outbreaks. *Atmos. Chem. Phys.*, 25, 15047–15076, https://doi.org/10.5194/acp-25-15047-2025 .

Profiles of thermodynamic and cloud properties and their transformations during Arctic Warm Air Intrusions (WAIs) and Cold Air Outbreaks (CAOs) were observed during an aircraft campaign, and simulated using the ICON weather prediction model. The data were collected along flight patterns aimed at sampling the same air parcels multiple times, enabling Eulerian and quasi-Lagrangian measurement-model comparisons and model process studies. Within the Eulerian framework, the temperature profiles agreed well with the ICON output although a small model bias of −0.9 K was detected over sea ice during CAOs. Also, the air parcels did not adjust to the changing surface skin temperature quickly enough. The specific humidity profiles were reproduced by ICON with mean deviations of 6.0 % and 19.5 % for WAIs and CAOs, respectively. Radar reflectivities based on ICON output captured the vertical cloud distributions during the airmass transformations. The simulated process rates of temperature and humidity along the trajectories showed that adiabatic processes dominated the heating and cooling of the air parcels over diabatic effects during both WAIs and CAOs. Of the diabatic processes, latent heating and turbulence had a stronger impact on the temperature process rates than terrestrial radiative effects, especially over the warm ocean surface during CAOs. Finally, a quasi-Lagrangian observation-model comparison was performed. For WAIs, the observed change rates of temperature and humidity were not perfectly captured in the simulations. For the CAOs, the calculated heating and moistening change rates of the airmasses were well represented by ICON with remaining deviations close to the surface.

December 2025

ARTICLES

Castro, S. L., **G. A. Wick,** and A. T. Jessup (2025). Modulation of the ocean surface skin temperature and heat flux in the presence of strong SST fronts. *Journal of Geophysical Research: Oceans*, 130, e2025JC022713, https://doi.org/10.1029/2025JC022713.

> Previous studies of air-sea interactions over sharp oceanic fronts have suggested that it is the ocean that drives the atmosphere across sub-mesoscale ocean fronts, but it is the atmosphere that drives the ocean at synoptic scales; the responsible mechanism, however, is still a matter of debate. This paper examines direct sea surface temperature (SST) measurements of the skin (SST_{skin}) and near-surface SST ($SSTd_{epth}$), and wind speeds measured during the Sub-Mesoscale Ocean Dynamics Experiment (S-MODE) along with derived bulk fluxes. We evaluate the modulation of the net heat flux, wind speed, and skin cooling across SST fronts and the ability of the COARE bulk flux algorithm to reproduce this variability. Bulk flux computations can be performed directly from a radiometric SST_{skin}, or more commonly, from the SST_{depth} provided that the depth of the SST measurement is corrected for cool skin and diurnal warming effects. Both types of SST were measured during S-MODE allowing for (a) an assessment of the importance of having a SST_{skin} for a direct flux evaluation in frontal regions, and (b) an evaluation of the accuracy of the cool skin and diurnal warming corrections within COARE for the indirect bulk flux computation. The ocean-atmosphere feedback over the sampled S-MODE submesoscale front suggested that the ocean was indeed forcing the atmosphere, mainly through the surface net heat losses, while the wind response to changes in SST_{skin} was irregular. Testing of the COARE algorithm suggested that indirect bulk fluxes had sufficient accuracy to close the heat budget over the front.

Jung, T., ... **M. D. Shupe**,...**T. Uttal**, et al. (2025). Year of Polar Prediction (YOPP): Achievements, Impacts, and Lessons Learnt. *Bull. Amer. Meteor. Soc.*, 106, E2519–E2543, https://doi.org/10.1175/BAMS-D-23-0226.1.

> The Year of Polar Prediction (YOPP), an international research initiative organized by the World Meteorological Organization's (WMO) World Weather Research Program from 2013 to 2022, aimed to markedly enhance environmental prediction capabilities in the polar regions and beyond, particularly in the context of a rapidly changing climate. YOPP achieved this through a concerted effort in observation, modeling, verification, user engagement, and educational activities. This article offers a comprehensive overview of YOPP's key outcomes and impacts, using a dual approach that merges qualitative success stories with quantitative metrics. Scientifically, the focus is on the role of polar observations in improving prediction accuracy, enhanced understanding of processes to support model development, advancements in forecast verification, particularly in sea ice prediction, an improved understanding of the interconnections between polar and midlatitude regions, and effective user engagement. This paper also discusses how these scientific discoveries have been converted into practical applications, emphasizing the route from science to services. Additionally, it summarizes the education, communication, outreach, and coordination efforts employed to maximize YOPP's impact. Finally, the article provides a series of recommendations for future research, informed by the insights gained from YOPP's experiences and recent radical developments in technology.

Martinez-Villalobos, C., **A. Capotondi**, C. Deser, B. Dewitte, N. J. Holbrook, **M. Newman**, **C. Penland**, D. J. Vimont and A. Wittenberg (2025). A low-order data-driven model of ENSO diversity. *Geophysical Research Letters*, 52, e2025GL118649, https://doi.org/10.1029/2025GL118649.

> Linear Inverse Models (LIMs) are widely used data-driven tools for studying El Niño Southern Oscillation (ENSO). However, standard LIMs struggle to simulate the observed asymmetry and diversity of ENSO events. Observations reveal that strong Central Pacific (CP) La Niñas and extreme Eastern Pacific (EP) El Niños occur more frequently than their counterparts, a feature standard LIMs fail to capture. We introduce a modified model, the Non-Gaussian LIM (NG-LIM), which transforms the LIM variables to better simulate ENSO asymmetry and diversity. Specifically, the NG-LIM reproduces the spatial pattern of sea surface temperature (SST) skewness and the inverted U-shaped relationship between the first two principal components of Tropical Pacific SST anomalies, reflecting more frequent strong CP La Niñas and extreme EP El Niños. NG-LIM simulations also show El Niños that are stronger and evolve more rapidly than La Niñas. This improved inverse model generates synthetic events to supplement the limited observational record.

Sardeshmukh, P. D., **C. Penland** and **G. P. Compo** (2025). Learning ENSO Dynamics from Data. *J. Climate*, 38, 7437–7452, https://doi.org/10.1175/JCLI-D-25-0053.1.

Much of the predictability of seasonal climate anomalies around the globe is due to the predictability of tropical El Niño–Southern Oscillation (ENSO) events and their global teleconnections. Despite decades of research, however, the relative roles of the dominant positive and negative feedbacks on predictable ENSO event magnitudes, patterns, and durations remain unclear. Here, an attempt is made to estimate these feedbacks directly from observational data. A 15-component linear inverse model (LIM) of the coupled Indo-Pacific atmosphere–ocean climate system is constructed for this purpose using reanalysis data for 1979–2017, and its predictable dynamics are clarified through a series of feedback-denial experiments. This approach yields, for the first time from data, a clear picture of the dominant competition between the destabilization of ENSO by positive near-surface zonal wind and subsurface oceanic feedbacks and its stabilization by a negative surface shortwave flux feedback associated with cloud shielding in cloudy areas. The results suggest that it is primarily this negative feedback that renders ENSO asymptotically stable. They also suggest that its underrepresentation is likely behind the tendency of climate models to extend the equatorial Pacific warming during El Niño (and cooling during La Niña) too far west into the western Pacific, compromising seasonal and longer-term predictions around the globe. An underrepresentation of this negative feedback over the Maritime Continent is also consistent with the mean sea surface temperature (SST) cold tongue and easterly trade wind biases of many climate models over the western equatorial Pacific.

Slivinski, L. C. and **J. S. Whitaker** (2025). Investigating the impact of rapid cycling in a global data assimilation system. *Mon. Wea. Rev.*, 153, 2933–2945, https://doi.org/10.1175/MWR-D-25-0097.1.

Most operational weather prediction centers cycle their global data assimilation systems at a cadence of two to four times per day for global weather prediction. Increases in computing power, observation availability, and horizontal model resolution motivate the development of a more rapidly updated global assimilation system. Experiments using hybrid four-dimensional ensemble-variational data assimilation (4DEnVar) with 1-h assimilation windows are performed in a version of the NOAA Global Data Assimilation System, and results are compared to those from traditional 6-hourly cycling. Skill is evaluated via comparisons with in situ observations, satellite winds, and regional analyses. Ensemble mean forecasts initialized from the hourly cycled fields show significantly better skill for some variables and regions than those initialized from traditional 6-hourly cycled fields, though they are informed by the same observations. These benefits appear only when dense, accurate observations are assimilated (e.g., aircraft wind). When aircraft data are withheld from assimilation, hourly cycling degrades the fit to in situ observations. Investigations into kinetic energy spectra demonstrate that fields from the hourly cycling system retain more energy at synoptic and subsynoptic scales than fields from the 6-hourly cycling system. These results suggest that a global hourly cycling assimilation system can use temporally and spatially dense observations more effectively than a 6-hourly cycling system

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