PHYSICAL SCIENCES LABORATORY

# Physical Sciences Laboratory (PSL) Publication Report

## July through September 2026

23 articles, 1 report

A list of PSL-affiliated articles, datasets, and reports with abstracts from FY26 Q4. Listed alphabetically by lead author. PSL-affiliated authors at time of authorship in **bold.**

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## July 2026

### ARTICLES

Benedict, J., **B. Wolding**, W. Hannah and C. DeMott (2026): Subseasonal tropical convection characteristics in the Energy Exascale Earth System Model version 2. *Journal of Geophysical Research: Atmospheres,* **131**, e2025JD046002, https://doi.org/10.1029/2025JD046002.

Accurate simulation of subseasonal tropical moist convection remains a key challenge for Earth system models. The difficulties stem from the reliance of cumulus cloud processes on model parameterizations and the need to represent the multiscale nature of interactions among clouds, radiation, moisture, circulation, and surface energy fluxes. Equatorial convection drives circulation anomalies that can affect weather patterns and extremes globally, motivating efforts to better understand and simulate these tropical disturbances. Here, a detailed review of subseasonal tropical convective behavior as simulated in the Energy Exascale Earth System Model version 2 (E3SMv2) is presented, with comparison to its predecessor version 1 (E3SMv1) and reference data sets. Model structural changes to the deep convective trigger function and surface fluxes, along with parametric tuning of the cloud and microphysics schemes, together result in an improved depiction of organized tropical convection across scales. In particular, E3SMv2 exhibits a more realistic Madden-Julian oscillation (MJO) and low-frequency Kelvin waves—owing to a sharper time mean equatorial meridional moisture gradient and improved convection-circulation coupling —as well as a better depiction of MJO Northern Hemisphere teleconnections. Despite these improvements, subseasonal precipitation variance continues to be strongly underestimated in E3SMv2. Use of a cloud plume model also reveals that the coupling between daily averaged tropical precipitation and lower tropospheric instability in E3SM is inconsistent with observations, a bias that could potentially impact the simulation of intraseasonal disturbances.

*Plain Language Summary:* Moist convective storm systems in the tropics naturally emerge on a wide range of space and time scales. Many Earth system models struggle to accurately simulate these features, mainly due to the challenge of representing complex interactions between clouds and their environment. Accurately simulating these disturbances is important because they strongly impact weather patterns and extremes both within the tropics and in the middle and high latitude regions. Here we review how well E3SM version 2 (E3SMv2) simulates tropical convective storm systems, and compare the results to its predecessor version 1 (E3SMv1) and observations. Compared to E3SMv1, updates to the representation of cloud processes and surface energy exchanges in E3SMv2 ultimately improve simulation of the larger cloud systems and their impacts on middle and high latitude weather patterns. However, important differences between E3SMv2 and observational data sets remain. E3SMv2 produces tropical precipitation variance that is considerably too weak, and interactions between rainstorms and the lower atmosphere conditions are different from observations. Such differences could result in less accurate simulations of larger convective storm systems.

Bodini, N., S. Letizia, **B. Adler**, D. D. Turner, R. Krishnamurthy, A. Scholbrock, D. Jager, E. Cinquino and A. Kirincich (2026): Observations of offshore low-level jets off the U.S. East Coast reveal systematic biases in ERA5 and HRRR. *Geophys. Res. Lett.*, **53**, e2025GL119969, https://doi.org/10.1029/2025GL119969.

Low-level jets (LLJs)—wind speed maxima typically occurring a few hundred meters above the surface—are common off the U.S. East Coast and influence many atmospheric processes with societal importance, including cloud formation, aviation safety, and search-and-rescue. However, their vertical structure and frequency remain poorly quantified due to limited offshore observations. This study presents new scanning Doppler LiDAR and infrared spectroradiometer data from the 2024 summer deployment of an offshore barge during the Wind Forecast Improvement Project 3. These coupled wind and temperature profiles provide unprecedented resolution to assess LLJ behavior and model performance. LLJs occurred in over 21% of observed profiles, with a weak diurnal preference for nighttime and early morning hours and maximum winds typically near 300 m. Both ERA5 and High-Resolution Rapid Refresh analysis underestimate jet wind speeds and misrepresent the boundary layer thermal structure. These results highlight persistent model biases and the critical need for high-resolution offshore observations.

*Plain Language Summary:* Understanding how wind behaves just above the ocean surface is essential for many applications: weather prediction, aviation safety, and search-and-rescue. One key feature in this environment is the low-level jet (LLJ)—a layer of fast-moving air a few hundred meters above the sea. LLJs can change how much power wind turbines produce and affect how weather models predict wind conditions. However, scientists so far have had limited opportunities to observe LLJs in detail over the ocean, especially far from land. In this study, we used advanced instruments placed on a barge off the coast of Massachusetts and Rhode Island to measure wind and temperature profiles up to a few kilometers above the ocean surface throughout summer 2024. We found that LLJs occurred over 21% of the time and peaked around 300 m high. We then compared these measurements with widely used weather models and discovered that both models underestimated the strength of LLJs and did not capture the layering of temperature as well as the observations did. These results show why high-quality offshore measurements are so important: they help improve models that guide weather forecasting over the ocean.

**Gehne, M.**, **J. Dias**, **J. D. Scott**, **D. J. Amaya**, **M. G. Jacox**, **M. A. Alexander** and AA Cluett (2026): Influence of Atmospheric Errors on Weeks 2-4 California Current System predictions. *Mon. Wea. Rev.*, **154**, 1427–1441, https://doi.org/10.1175/MWR-D-26-0009.1.

Understanding the forecast skill of ocean state anomalies on subseasonal time scales is critical for the effective use of ocean forecasts in marine resource management. Here, we evaluate error propagation in the European Centre for Medium-Range Weather Forecasts subseasonal to seasonal (S2S) coupled forecast system, specifically examining how atmospheric errors impact the accuracy of California Current System (CCS) ocean forecasts. Ensemble sensitivity analysis reveals regions where early lead-time atmospheric conditions can influence upper-ocean forecast errors, particularly in sea surface temperature and mixed layer depth. Conditioning on ensemble members with smaller atmospheric errors during the first 1–4 lead days yields a reduction in CCS errors for lead weeks 2–4 which is statistically significant for weeks 2–3. Improvements in the strength of both low and high pressure systems lead to better representation of near-surface alongshore winds, which constitutes improved atmospheric forcing of CCS ocean conditions. Here, we show how atmospheric weather patterns modulate the upper CCS by diagnosing the propagation of model errors in an operational S2S coupled forecast system. These results suggest that identifying more predictable atmospheric states early in the forecast can lead to more accurate CCS predictions for weeks 2–3.

*Significance Statement:* The oceanic region along the west coast of North America is a highly productive large marine ecosystem. Marine resource management balances human uses such as fishing, shipping, and tourism, with marine species and habitat conservation for future generations. Knowledge of the skill of forecasts of oceanic conditions in this region on time scales of several weeks is, therefore, of interest to marine resource management. In particular, advance knowledge of the timing of spring upwelling events and associated nutrient rich waters could provide information for fisheries on marine species distribution. Here, we show that forecasts associated with a better representation of weather patterns early in the forecast result in subsequent more accurate California Current System ocean state predictions. Our study suggests that improved weather forecasts over the northeast Pacific and western United States at earlier times are a promising pathway for more accurate oceanic weeks 2–4 predictions along the west coast of North America.

Jeffree, J., N. Maher, **D. J. Amaya** and D. Dommenget (2026): Adapting analogue forecasting to compare ENSO remote influences across different models and regions. *Clim Dyn,* **64**, 327, https://doi.org/10.1007/s00382-026-08258-1.

The El Niño Southern Oscillation (ENSO) is a tropical Pacific phenomenon influenced by climate anomalies in other regions of the world. We compare the impacts on ENSO from regions external to the tropical Pacific with a new unifying multi-model framework. This framework adapts analogue forecasting to identify the improvement in perfect-model ENSO forecast skill when including information from regions outside the equatorial Pacific. We use this methodology to investigate the relative influence on ENSO from each of the tropical Atlantic, tropical Indian, and north and south tropical Pacific Oceans, and the differences in how these influences are simulated by 12 state-of-the-art coupled climate models. In most models, ENSO forecast skill is improved by information from ocean regions external to the equatorial Pacific, implying that these regions contain independent variability that impacts ENSO evolution. Overall, the largest skill increases come from information in the Atlantic Ocean, followed by the Indian, south Pacific, then north Pacific Oceans. The influence on ENSO of these four ocean regions peaks between 6 and 18 months lead time. However, the magnitude of skill increase depends on the specific model, lead time and forecast initialisation month. We find almost no skill increase from information in any region poleward of 30°. Finally, we note that the GFDL-CM2.1 model used for many pacemaker studies exhibits the weakest remote influences on ENSO of any model we consider. Our results, and this method which may be applied to other models, lay the groundwork for contextualising and comparing studies of remote influences on ENSO in individual climate models.

**Pfohl, A.K.D.**, **W. R. Currier**, E.N. Boardman, J. M. Pflug and **M. R. Abel** (2026): Investigating the Effects of Spatial Snow Water Equivalent Heterogeneity on Runoff Timing and Magnitude. *Hydrological Processes*, **40** (7), e70659, https://doi.org/10.1002/hyp.70659.

Mountain snowpack spatial variability can impact snow-driven streamflow timing and magnitude. Near-peak, lidar-derived snow water equivalent (SWE) data were coarsened (50 m through 1 km re-gridding and elevation bands) and inserted into the Distributed Hydrology Soil Vegetation Model (DHSVM) to evaluate how spatial snow heterogeneity influences streamflow in the Tuolumne River, California, and Blue River, Colorado. In the Tuolumne, simulated peak streamflow from the most homogeneous snowpack representation was 36% greater than the more heterogeneous simulations. In all years, the homogeneous snowpack representation did not produce an observed snowmelt pulse in the recession limb. Streamflow during late summer was higher (up to 3.5 times) for finer-resolution snow heterogeneity simulations. In the Blue, sensitivity to snowpack heterogeneity was less pronounced. This difference between watersheds was attributed to differences in spatial snowpack patterning and subsurface processes between the two basins. In the Blue, snowmelt infiltrated into the subsurface and was slowly released throughout summer. In the Tuolumne, mid-winter melt and rain resulted in higher soil moisture at peak SWE. The combination of high antecedent soil moisture and the Tuolumne's subsurface characteristics contributed to flashier snowmelt runoff compared to the Blue. For both watersheds, altering snow heterogeneity had little effect (within 2%) on total end-of-water-year runoff or evapotranspiration because absolute differences balanced out throughout the melt season: A more heterogeneous SWE representation produced less streamflow at peak SWE but greater streamflow afterward relative to a coarser SWE representation. Experiments isolating radiation variability demonstrated that accumulation heterogeneity at peak SWE had a stronger influence on streamflow timing than post-peak radiation heterogeneity. These results suggest that if basin-mean SWE is well constrained, capturing spatial heterogeneity in SWE may not be necessary for water supply forecasting on quasi-annual timescales but may be important for simulating late summer flows, snow cover persistence, and magnitude of peak flows.

Smith, S. R., M. A. Bourassa, M. Castells, A. Lovett, E. M. McDonald, T. Vedagiri, V. Tsontos, J. T. Roberts, F. Platt, **L. Bariteau**, **E. J. Thompson** and **C. W. Fairall** (2026): MarineFlux: A Data Service for Shipboard Air-Sea Fluxes. *Geosciences Data Journal*, **13** (3), e70087, https://doi.org/10.1002/gdj3.70087.

The MarineFlux project is providing access to direct and bulk turbulent air–sea flux observations via an Environmental Research Division's Data Access Program (ERDDAP) service and a graphical user interface, known as the MarineFlux Explorer. These services are designed to meet the needs of the air–sea flux community for in-situ flux observations. Results of a community survey are discussed which partially define the community requirements. The data dissemination, analysis and visualization services described presently include fluxes derived from the International Comprehensive Ocean–Atmosphere Data Set for 1990–2020, the Shipboard Automated Meteorological and Oceanographic Systems (SAMOS) initiative for 2005–2024, and select flux datasets from NOAA Physical Science Laboratory expeditionary cruises from 1991 to 2021. The overall architecture for the services is described along with examples of how to access and use both the ERDDAP and Explorer interfaces.

**Swenson, L. M.**, **B. J. Moore** and **K. M. Mahoney** (2026): Atmospheric Rivers in Machine Learning Weather Models. *Wea. Forecasting*, **41**, 1313–1329, https://doi.org/10.1175/WAF-D-25-0142.1.

This study examines the representation of atmospheric rivers (ARs) in medium-range forecasts (1–10-day lead time) from machine learning weather prediction (MLWP) models. ARs pose high-impact consequences, both in terms of flooding and their contributions to water resources. As MLWP models proliferate, there is a pressing need to understand MLWP model skill for AR prediction. ARs provide a useful test case for MLWP models because they are filamentary features exhibiting large gradients in thermodynamic and kinematic fields that may not be well represented within the machine learning loss function framework. We evaluate and compare forecasts from two deterministic MLWP models, GraphCast and Pangu-Weather, with two operational numerical weather prediction (NWP) models, NOAA's Global Forecast System (GFS) and ECMWF's Integrated Forecasting System (IFS). We focus on wintertime ARs in the northern Pacific over lead times from 1 to 10 days and employ a combination of gridpoint-based as well as novel, object-based verification methods. We also use storm-relative composites of thermodynamic and kinematic fields to diagnose strengths or shortcomings in the emulation of physical processes. Results show that MLWP models can represent ARs well according to certain aggregate metrics, with some caveats and systematic differences compared to traditional NWP models. The ARs in MLWP models are slightly too weak and too small compared to both reanalysis and NWP models. MLWP models differ systematically from NWP models in the biases of dynamic and thermodynamic fields within strong ARs. Better understanding phenomena-specific traits of MLWP models can help improve both forecaster interpretation of their predictions and inform improvements to both MLWP and NWP forecasts.

Yang, X., ..., **P. O. G. Persson**, et al. (2026): Polar winter processes: An under-represented research focus within the coupled Earth system. *Adv. Atmos. Sci.*, https://doi.org/10.1007/s00376-026-6256-5.

Observing winter processes during the extended cold season is crucial not only for understanding polar and global coupled Earth system but also for enhancing capability of year-round prediction, especially in the context of Arctic amplification and the drastic decrease in sea ice extent and thickness at both poles. However, harsh environmental conditions and logistical challenges have left polar winter Earth system processes substantially under-observed compared with those during summer. This disparity creates major obstacles for studying these processes and their roles in shaping the state and variability of the Earth systems, as well as for accurately simulating them in Earth System Models (ESMs). Consequently, these limitations introduce considerable uncertainties in ESMs regarding the understanding, prediction, and projection of Earth system variability and changes. This study discusses key polar winter processes and evaluates critical knowledge gaps. It identifies three urgent research priorities for the near future: (i) sources, properties, and transport of polar winter aerosols and their interactions with clouds; (ii) polar storms and their interactions with the underlying sea ice and ocean; and (iii) persistent discrepancies in understanding and predicting large-scale teleconnections between polar regions and lower latitudes. To address these priorities, this perspective recommends strengthening coordinated, winter-focused, international and multidisciplinary observational efforts, for example, through initiatives such as the Fifth International Polar Year and the ongoing international Antarctica InSync programme. These initiatives would lay groundwork for designing future sustainable winter process observations.

## REPORTS

Tiwari, A., **J. L. Bytheway**, K. Knipper and A. Yanez (2026): Learning from Hydrometeorological Extremes: Research, Operations, and Communication. *Bull. Amer. Meteor. Soc.*, **107**, E1684–E1691, https://doi.org/10.1175/BAMS-D-26-0144.1.

Three panelists with backgrounds in academia, operations, and science communication came together at the AMS Annual Meeting Hydrology Town Hall Event titled "*Lessons Learned from Hydrometeorological Extremes: Past, Present and Future*" to share their experiences with hydrometeorological extremes. Their insights helped form key takeaways and guide future efforts. The session was held in an open town hall format, followed by audience questions.

# August 2026

## ARTICLES

Anderson, W., I. Becker-Reshef, N. Bodanac, B. Carneiro, D. English, **A. Hoell,** T. Hoffine, Y. Y. Liu, M. Machefer, M. Meroni, C. Raleigh, A. Tatem, R. Trigwell, P. Vesco and R. Vos (2026): Responsible use of artificial intelligence and machine learning for food security early warning systems. *Nat Food*, **7**, 736-739 https://doi.org/10.1038/s43016-026-01400-6.

> Artificial intelligence and machine learning are already enhancing food security early warning systems by improving data collection, event monitoring and forecasting. However, to avoid costly errors, artificial intelligence and machine learning should be applied selectively alongside expert oversight, robust governance and transparent practices to maintain accountable and effective humanitarian decision-making.

Angot, H., . . ., **L. Bariteau**, . . ., **B. W. Blomquist**, . . ., **C. J. Cox,** . . ., **P. O. G. Persson**, . . ., **M. D. Shupe**, et al. (2026): Influence of warm and moist air intrusions on black carbon deposition and snowmelt in the central Arctic. *Elem Sci Anth,* **14** (1), 00124, https://doi.org/10.1525/elementa.2025.00124.

> In the central Arctic, warm and moist air intrusions (WAMIs) are increasingly prevalent during winter and spring, significantly affecting the near-surface energy budget. Here, we combine in situ observations from the 2019–2020 Multidisciplinary drifting Observatory for the Study of Arctic Climate (MOSAiC) expedition with model simulations to investigate the role of WAMIs in transporting pollutants and enhancing black carbon (BC) wet deposition. Several WAMI episodes were associated with elevated ambient BC concentrations, and the model indicates that these events lead to an average of approximately 40% increase in BC wet deposition compared to typical winter–spring conditions. To assess the potential implications of this deposition for the cryosphere, we performed a set of sensitivity experiments using the SURFEX/ISBA-Crocus multilayer snowpack model. These experiments allowed isolating the impact of enhanced BC deposition, indicating that WAMI-driven inputs can increase solar energy absorption by 3–5 $W/m^2$ on average and accelerate snowmelt rates by more than 20% during the following summer. These simulations offer process-based insights on the influence of episodic pollution transport events on snow and climate feedbacks. These findings underscore the need for targeted and spatially distributed measurements of BC in central Arctic snowpacks—away from potential local contamination sources (e.g., ship exhaust)—to better constrain the role of WAMIs in Arctic snow and climate processes.

**Breeden, M. L.** and **R. P. Worsnop** (2026): Subseasonal-to-Seasonal Wildland Fire Prediction and Predictability in the Contiguous United States. *US CLIVAR Variations*, **21**, 18-23, https://doi.org/10.5065/8cyx-yw96.

> Breeden and Worsnop examine the complexities of predicting wildland fire danger on subseasonal-to-seasonal timescales across the contiguous United States, detailing how large-scale climate drivers like the El Niño-Southern Oscillation and long-term warming trends influence predictability. They highlight that forecast skill varies significantly among fire-relevant variables, such as vapor pressure deficit and the energy release component, largely depending on the underlying signal-to-noise ratio of each variable across different seasons and lead times. Ultimately, the authors identify critical knowledge gaps and future research questions needed to reduce systematic model biases and improve advanced fire risk forecasting.

**Cox, C. J., A. Solomon,** M.S. Town, **M. D. Shupe**, D. Clemens-Sewall, N. Fuchs, **M. R. Gallagher**, D. K. Perovich, **P. O. G. Persson**, **A. Sledd** and V. P. Walden (2026): Resiliency of Arctic sea ice to warming from southerly advection in early spring. *Elem Sci Anth*, **14** (1), https://doi.org/10.1525/elementa.2026.00027.

> Summertime surface melt over sea ice was observed in situ by the Multidisciplinary drifting Observatory for the Study of Arctic Climate (MOSAiC) on May 25, 2020. The melt was initiated by longwave radiative forcing from a warm, cloudy air mass advected from lower latitudes, similar to that observed in 1998 during the Surface Heat Budget of the Arctic Ocean in the Beaufort Sea. In addition to triggering melt onset, research suggests that springtime atmospheric advection may also precondition Arctic sea ice for melt onset by rapidly increasing its internal energy. In keeping with this, we find that an advection event in April 2020 delivered 42% of the springtime increase in internal energy the MOSAiC ice floes underwent prior to melt onset. However, we argue that the potential for this preconditioning to affect the melt onset date is limited. We test whether the energy retained within the snow/ice column from the event was significant relative to the hypothetical scenario that the event did not reach MOSAiC. We apply both observed surface temperatures and counterfactual (simulated) ones characterized by the event's

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absence to a diffusion model representing the snow and ice. We find that the energy storage anomaly in the ice from the event decays rapidly relative to the scenario that omits advection (e-folding time 6.9 days). This diminishing impact is because the initial warming reduces the temperature gradient in the ice column, creating a negative feedback that suppresses heating thereafter. The influence of the April advection dissipated in the ice several weeks prior to melt onset. A more important precursor to melt onset may be the date of persistently positive atmospheric forcing, which causes convergence of flux within the ice. These results imply that negative feedbacks associated with heat conduction are a moderating factor to the beginning of the melt season.

Dukhovskoy, D. S., T. Cordero, K. Hedstrom, M. A. Alexander, **M. G. Jacox**, R. Hallberg, M. J. Harrison and **J. Liu** (2026): Design and Implementation of a Newtonian Relaxation Scheme in the NOAA GFDL Sea Ice Model (SIS2). *Geosci. Model Dev.*, **19**, 7169–7196, https://doi.org/10.5194/gmd-19-7169-2026.

Regional sea ice models often do not cover the full extent of polar ice and instead include open ocean boundaries that are not ice-free year-round. This necessitates the specification of lateral boundary conditions for sea ice, an inherently challenging task for most sea ice models. Although this issue is less critical for pan-polar domains, the interior ice state still needs to be constrained for many applications. In this study, we present the design and evaluation of a Newtonian relaxation algorithm for sea ice, implemented in the NOAA Geophysical Fluid Dynamics Laboratory (GFDL) Sea Ice Simulator (SIS2). The algorithm can be applied both at the lateral boundaries to impose open boundary conditions and within the interior domain to constrain sea ice thickness and concentration toward prescribed target fields. The method is flexible and can be applied anywhere in the domain, making it especially well-suited for regional applications of sea ice models with variable ice cover along their boundaries. The method is evaluated within a regional forecasting system based on the NOAA GFDL ocean model (MOM6) coupled with sea ice model (SIS2) for two regional configurations: the Northeast Pacific and the Arctic Ocean. Sensitivity experiments spanning a range of relaxation time scales and nudging strengths demonstrate that the method substantially improves the representation of sea ice and associated ocean surface fields, offering a practical solution for both boundary and interior constraints in regional sea ice modeling.

**Kiladis, G. N.** and R. A. Madden (2026): Structure, Propagation and Variability of the 5-Day Rossby-Haurwitz Wave. *Journal of Geophysical Research*, **131**, e2026JD047325, https://doi.org/10.1029/2026JD047325.

The 5-day wave is the gravest free Rossby mode predicted by the Laplace shallow water equations, with a latitudinally symmetric, zonal wavenumber one theoretical structure in geopotential extending from pole to pole. It propagates westward along the equator at about 98 m $s^{-1}$ and was first observed in surface pressure data during the 1950s. Since then, it has been shown to modulate tropical precipitation, sea level and bottom ocean pressure, stratospheric ozone and water vapor, and noctilucent clouds and water vapor in the polar mesosphere. There is still much to be learned about the 5-day wave. We confirm previous observational results suggesting that most 5-day wave events start near the earth's surface around Antarctica, where it initially has a strongly northwest-to-southeast tilted structure confined to the Southern Hemisphere. The wave then propagates northward to eventually encompass the entire globe in around a week, when its structure more closely resembles its freely propagating theoretical counterpart. At the same time, the wave's energy propagates upward into the middle atmosphere, reaching 80 km height in around 10 days with a height-dependent upward group velocity inversely proportional to the static stability parameter $N^2$. This evolution is dominant at all times of the year, with wave activity peaking at the equinoxes. Although the longitudinal position of baroclinic waves in the Southern Hemisphere storm track is weakly synchronized to the zonal phase of the 5-day wave, episodes of enhanced 5-day wave activity appear to be excited by anomalously strong baroclinic wave activity further south around Antarctica.

*Plain Language Summary:* The 5-day wave is a global scale atmospheric disturbance that extends from pole-to-pole and across all longitudes, which was first observed in surface atmospheric pressure data during the 1950s. It propagates rapidly westward along the equator at nearly 100 m $s^{-1}$ (or around 360 km $hour^{-1}$), and has been shown to modulate tropical precipitation, sea level and ocean bottom pressure, stratospheric ozone and water vapor, and extremely high (noctilucent) clouds and water vapor in the mesosphere up to and beyond heights of 80 km. We confirm previous observational results suggesting that most 5-day wave events start near the earth's surface around Antarctica, then propagate northward eventually encompassing the entire globe in around a week. At the same time, the wave's energy propagates upward into the middle atmosphere and thermosphere, reaching a height of 80 km in around 10 days. We also demonstrate that storm activity around Antarctica excites the 5-day wave at all times of the year. Understanding the detailed evolution of the 5-day wave is important for processes that modulate tropical precipitation and sea level, as well as water vapor and trace gases at all levels of the atmosphere.

Kulkarni, S., K. A. Schiro, G. S. Elsaesser, A. F. Adames Corraliza, F. Ahmed, J. D. Neelin and **B. Wolding** (2026): Investigating Thermodynamic Controls on Tropical Mesoscale Convective System Life Cycles. *J. Atmos. Sci.*, **83**, 1485–1504, https://doi.org/10.1175/JAS-D-25-0137.1.

Determining which meteorological conditions support the upscale growth and organization of individual deep convective cells into clusters on the order of hundreds of kilometers—known as mesoscale convective systems (MCSs)—is critical to our understanding and prediction of heavy precipitation. Here, we perform a comparative statistical analysis of thermodynamic environments surrounding organized deep convection (MCSs) as sampled in both space and time by three different atmospheric sounding sources: 1) NASA's Aqua satellite, 2) the Department of Energy's Atmospheric Radiation Measurement (ARM) Program, and 3) reanalysis. First, we examine pre-MCS conditions up to 12 h before MCS detection. Then, we use tracked MCS data to examine changes in the thermodynamics as MCSs evolve through growth, mature, and decay stages. Our results suggest that the free troposphere (FT) moistens and the boundary layer (BL) warms within 12 h ahead of MCS detection, enhancing instability with respect to an entraining plume and supporting the upscale growth of deep convection. Moreover, life cycle composites suggest that the BL (FT) becomes progressively drier and cooler (warmer and moister) as the MCSs decay, stabilizing the troposphere. Entraining plume buoyancy estimates can clearly distinguish between different MCS life cycle phases. Interestingly, spatial compositing of environments surrounding MCSs in Atmospheric Infrared Sounder (AIRS) data reveals a ring of enhanced BL moisture at MCS edges and a cool, dry MCS centroid, indicative of convergence at the leading edge of cold pools enhancing buoyancy and supporting upscale growth. These signatures are largely absent in the fifth generation European Centre for Medium-Range Weather Forecasts (ECMWF) atmospheric reanalysis (ERA5), however. Finally, comparing larger, longer-lived ("more organized") systems to smaller, shorter-lived ("less organized") systems highlights the importance of free-tropospheric humidity as a critical control on deep convection organization (as defined here), as free-tropospheric moisture is comparatively enhanced ahead of larger, longer-lived systems while the lapse rate instead favors increased stability.

Li, W., S. Sun, **L. Bengtsson**, M. Zhang, J. Dudhia, **E. Grell**, J. Simonson, T. Hertneky and L. Nance (2026): Layer-Dependent Diurnal Moist Static Energy Biases in the Unified Forecast System During the MJO Preconditioning Stage: A DYNAMO Case Study. *Journal of Geophysical Research: Atmospheres*, **131**, e2026JD046470, https://doi.org/10.1029/2026JD046470.

Accurate simulation of the Madden-Julian Oscillation (MJO) requires realistic diurnal evolution and vertical distribution of moist static energy (MSE). While prior studies documented MSE bias in simulations, vertically dependent physical processes responsible for these biases remain insufficiently understood. This study applies a hierarchical modeling and evaluation approach, combining fully coupled Unified Forecast System (UFS) forecasts with observation-constrained single-column model (SCM) experiments, to enable vertically and diurnally resolved assessment of MSE during two MJO events from the DYNAMO field campaign. Results reveal a diurnal loop of layer-dependent biases: daytime errors precondition nighttime residual energy, which in turn influences MSE and convection on the following day. These biases are associated with deficiencies in the convective parameterization, in which convective latent heating is concentrated in the upper troposphere while the transition layer receives insufficient energy input, reflecting a missing shallow-to-deep convective transition. The convective parameterization also converts cloud condensate, especially ice, too efficiently, reinforcing an overly top-heavy energy structure. This residual energy aloft persists overnight, suppressing the re-establishment of low-level instability and limiting convective development the following day. This hierarchical, vertically resolved analysis provides a process-based pathway for diagnosing issues in tropical energetics on the diurnal timescale during the MJO preconditioning stage, with potential implications to improve MJO prediction in the UFS and related forecast systems.

*Plain Language Summary:* Realistic simulation of the Madden-Julian Oscillation (MJO) depends on accurately capturing the diurnal evolution and vertical distribution of moist static energy (MSE). However, the physical reasons of persistent MSE underestimation in global models remain poorly understood. This study employs a hierarchical modeling and evaluation approach that integrates fully coupled Unified Forecast System (UFS) forecasts with observation-constrained single-column model experiments. This approach is one of the first to systematically analyze how MSE changes diurnally and vertically in the atmosphere. The analysis reveals a coherent, layer-dependent chain of errors in the model physics, particularly in the convective parameterization. These errors limit vertical energy transport and accumulation, and prevent the smooth transition from shallow to deep convection, and the next-day convection development. By identifying the key sources of bias and showing how they evolve across the daily cycle, this work offers a process-based roadmap to improve tropical energy representations and MJO prediction in global forecast systems like the UFS.

Lundquist, J. D., **M. R. Abel**, **W. R. Currier** and **D. L. Jackson** (2026): Snow What? Strengths and Limitations of Different Snow Products in the Western U.S. Mountains. *Water Resources Research*, **62**, e2026WR043728, https://doi.org/10.1029/2026WR043728.

Reported values of average annual peak snow water equivalent (SWE) in the mountains of the western United States differ by more than a factor of five, from not enough water to fill Lake Mead, the largest reservoir in the region, to enough water to fill Lake Mead five times. These products are not created equal. Many vastly underestimate snow water storage, and guidelines regarding which products are more accurate are crucial for using these products in any scientific analysis. Here, we review existing products and compare them to each other and to SWE derived from 26 aerial LiDAR acquisitions in Colorado, California, and Washington mountains of the western U.S. Products that match well with observations include (a) resolution of 9 km or finer, (b) reliance on observations of either fractional snow-covered area or in situ SWE measurements, and (c) a well-calibrated model framework that includes both quality precipitation estimates and accurate snowmelt. Many of the energy balance models reviewed had too much melt, likely from too much incoming radiation. Over all three regions, for the 14 flights that occurred close to peak SWE (March–April), the Western U.S. SWE Reanalysis (WUS-SR) is least biased in reproducing near-peak SWE (bias of 1.6%) and also best represented the spatial distribution of SWE (smallest mean absolute error). SNODAS and both of the University of Arizona products provide reasonable estimates (biases of 7.8%–10.2%). At the basin scale, ERA5-Land also has small bias (−17.5%), but due to its coarser resolution, less accurate spatial representations.

## September 2026

### ARTICLES

Aggarwal, P. K., C. Schumacher, F. J. Longstaffe, A. Funk and **M. D. Shupe** (2026): Isotopic fractionation during ice growth by riming and its effect on the *d*-excess of precipitation. *Atmos. Chem. Phys.*, **26,** 13661–13692, https://doi.org/10.5194/acp-26-13661-2026.

We have investigated the impact of riming on the deuterium excess ($d$-excess = $\delta^2H - 8 \cdot \delta^{18}O$) of precipitation. In mixed-phase clouds, precipitation forms by vapor deposition, where supercooled liquid droplets do not come in contact with ice particles, and by riming, where droplets freeze directly on particle surfaces. While vapor deposited ice generally has higher *d*-excess than liquid, riming is assumed to occur without isotopic fractionation. We correlated radar-observed mean Doppler velocity (MDV), an independent indicator of riming, with precipitation *d*-excess (−23 ‰ to +45 ‰) at polar (Summit, Greenland; Ny-Ålesund and Andenes, Norway, Dumont d'Urville, Antarctica), mid-latitude (Cazadero, California) and tropical (Rio Claro, Brazil) sites. The *d*-excess decreases with increasing MDV (or riming intensity) at all locations, except for winter precipitation at Summit. The low *d*-excess of rimed ice is consistent with the evaporation of accreted liquid on particle surface before freezing is complete. For Summit winter, cold temperatures and low $\delta^{18}O$ of vapor suppress *d*-excess independently of riming. Calculations show that mixtures of ice growing by riming and vapor deposition (including diamond dust) can produce the observed range of precipitation *d*-excess in this study. We conclude that riming-driven lowering of *d*-excess can explain, at least in part, the spatial gradients in surface snow *d*-excess across Greenland and Antarctica previously attributed to changes in source moisture origin, and the very low *d*-excess of rainfall attributed solely to sub-cloud evaporation. Precipitation *d*-excess can be used to estimate the rimed mass fraction, providing observational constraints for improving microphysics schemes in climate models.

Hartig, K., J. J. Cassano, **M. D. Shupe** and **A. Solomon** (2026): Cloud liquid water path at the North Slope of Alaska has minimal sensitivity to local meteorology in Arctic winter. *Atmos. Chem. Phys.*, **26**, 12689–12714, https://doi.org/10.5194/acp-26-12689-2026.

Mixed-phase clouds in the Arctic are tightly coupled to the surface energy budget in the cold months, helping to set surface temperatures and sea ice extent. However, the meteorological conditions that give rise to these clouds and their remarkable persistence across the Arctic are not well constrained, leading to model biases. Using over a decade of observations from the North Slope of Alaska, this research investigates the relationships between cloud base temperature and moisture, bulk atmospheric moisture, wind direction, large-scale circulation, and cloud liquid and ice water path. Liquid-containing clouds are ubiquitous at this site, occurring 60 %–70 % of the time between November and March, although about one-third of those cases have a liquid water path under 10 $g\,m^{-2}$. We find that liquid water path is weakly sensitive to temperature and moisture and remarkably insensitive to wind direction and large-scale circulation. Furthermore, meteorological regimes with significant differences in temperature, moisture, and cloud fraction do not produce appreciable differences in cloud liquid water path.

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Ice water path, on the other hand, is clearly correlated with bulk atmospheric moisture, with particularly strong increases when precipitable water vapor exceeds the 90th percentile, and may be responsible for the muted response of liquid water path to high atmospheric moisture. To explain the observed sensitivity of ice water path and relative insensitivity of liquid water path to meteorology and large-scale circulation, we propose a series of hypotheses centered around a lack of dissipative mechanisms and the role of ice in enabling or limiting liquid mass accumulation.

Reid, J. S., . . ., **E. J. Thompson,** et al. (2026): Delaminating the Marine Atmospheric Boundary and Saharan Air Layers: Observations and Modeling by MAGPIE to Understand Marine Boundary and Lower Free-Troposphere Layer Inhomogeneity over the Northwest Tropical Atlantic. *Bull. Amer. Meteor. Soc.*, **107**, E2276–E2306, https://doi.org/10.1175/BAMS-D-25-0224.1.

Simplifying the atmosphere into discrete layers, such as the marine atmospheric boundary layer (MABL) and its surface, mixed, and detrainment layers, as well as the Saharan air layer (SAL) aloft, is necessary in maritime meteorological modeling and data analysis. However, data reduction risks losing critical information. The Office of Naval Research (ONR) Moisture and Aerosol Gradients/Physics of Inversion Evolution (MAGPIE) experiment, centered on Ragged Point Barbados around August 2023, July 2024, and February 2025 used synthetic aperture radar (SAR), high-spectral-resolution lidar (HSRL), Doppler and Raman lidars coupled with ground-based instrumentation, and the Center for Interdisciplinary Remotely Piloted Aircraft Studies (CIRPAS)/NOAA aircraft to document the four-dimensional variability and large-to-fine-scale budgets of atmospheric state, clouds, sea salt, and dust. Results span three areas: 1) regime identification: SAR winds and geostationary imagery easily identify MABL regimes that can be reproduced in large-eddy simulations; 2) vertical exchange: Lidar and aircraft show that cloud organization of MABL regimes is related to vertical exchange from the near surface through cloud water vapor halos, especially at regime boundaries. Copious dust was also found in the MABL; and 3) SAL stratification: The concept of the monolithic or multilayer Saharan air is often realized as ultrafine Saharan air layer(s) stratified under influence by large-scale forcing, shear, diabatic heating, and likely more complex coupled processes. These insights inform multiscale modeling to bridge MABL "gray zone" processes too large for parameterization in large-domain models, yet too fine to be explicitly resolved due to computational constraints.

*Significance Statement:* While data reduction is necessary to analyze complex four-dimensional flows, oversimplification of atmospheric layers and their processes risks losing critical conceptual information and important model physics. The ONR Moisture and Aerosol Gradients/Physics of Inversion Evolution (MAGPIE) experiment deployed active remote sensing, aircraft, and shore-site instrumentation to capture the complex structure of the marine atmospheric boundary layer (MABL) and Saharan air layer (SAL). Findings reveal MABL cloud patterns are tied to vertical moisture exchange, significant dust exists within the MABL, and the SAL is a complex multilayer system, not monolithic. These crucial observations provide insights enabling refinement of multiscale models, more realistic simulations of airmass evolution, and significantly improved marine weather forecasts by bridging the gap between observations and "gray zone" modeling scales.

Thomas, R., **G. P. Compo**, S. George, G. Hegerl, A. Schurer, T. Shepherd, **L. C. Slivinski**, V. Thompson and E. Hawkins (2026): Everyday weather in a warmer world. *Earth Syst. Dynam.*, **17**, 1365–1380, https://doi.org/10.5194/esd-17-1365-2026.

How would the weather of a year from history be experienced in a warmer world? We reconstruct the weather of 1903 using a reanalysis system that assimilates only surface pressure observations (20CRv3) with observed SSTs, and then reconstruct it again with increased SSTs and atmospheric $CO_2$ levels. By assimilating the same pressure observations, the reanalysis experiments produce the same weather patterns, and so we translate the weather of 1903 into a warmer context. We focus on changes in the everyday weather of four regions with a high density of historical pressure observations, where the circulation is constrained and differences between the experiments are due to the thermodynamic component of climate change. In these regions, nearly all days are warmer in the warmer world experiments, but the largest increases occur on cold days (below freezing) and hot days (above 20 °C). Daily rainfall becomes more variable, even in regions where total rainfall is reduced. Fewer days experience light rain while more days experience heavy rain, and rainfall only increases on less than 1 d in 10. This single year pair of reanalysis experiments also recovers common patterns of observed and projected long-term changes. For example, Western Mediterranean precipitation declines outside winter, but shows a small increase in winter in the absence of storm track shifts. By anchoring our analysis in weather patterns that have actually occurred, the reanalysis experiments point to how our day-to-day experience of the same weather patterns may change in a warmer world, even if the weather patterns themselves do not.

**Toride, K.** , K. Yoshimura, M. Schneider, C. Diekmann, F. Khosrawi, B. Ertl and H. Bong (September 2026): The significance of water vapor isotopes in improving weather prediction. *Commun Earth Environ*, **7**, 695, https://doi.org/10.1038/s43247-026-03917-x.

Water vapor isotopes carry the integrated history of evaporation, condensation, mixing, and transport. Although previous studies have shown potential to improve forecasts under controlled conditions, real-world applications have been limited by systematic biases in both models and satellite retrievals arising from sparse measurements in the free troposphere. Here we assimilate mid-tropospheric δD retrievals (peak sensitivity ~4.2 km) from the Infrared Atmospheric Sounding Interferometer into the Isotope-incorporated Global Spectral Model and evaluate the added value beyond co-assimilated temperature and specific humidity with identical spatial and temporal coverage. Assimilating δD improves 0–120 h forecasts of wind, temperature, specific humidity, and geopotential height, with the largest gains in the midlatitudes; heavy-precipitation skill also increases for thresholds >3 mm per 6 h. Demonstrated in a coarse-resolution configuration with limited observations, the results indicate that isotopic information strengthens transport tracking and hydrological constraints, motivating evaluation in operational high-resolution forecasting systems.

Wang, X., P. J. van Leeuwen, P. Poterjoy, D. J. Stensrud, S. J. Greybush, Y. Zhang, H. Santer, Y. Wang, Z. Pu, X. Chen, B. C. Stouffer, S. Chiao, K. Ide, C.-H. Lu, A. Johnson, C. Liu, N. Gasperoni, Y. Yang, J. Kim, D. Kleist, **S. Frolov** and F. Carr (September 2026): The Multi-University Consortium for Advanced Data Assimilation Research and Education (CADRE). *Bull. Amer. Meteor. Soc.*, **107**, E2048–E2064, https://doi.org/10.1175/BAMS-D-25-0098.1.

The Multi-University Consortium for Advanced Data Assimilation Research and Education (CADRE) is a new initiative recently funded by the National Oceanic and Atmospheric Administration (NOAA) to accelerate data assimilation (DA) research, education, and workforce development. Unlike previous initiatives, CADRE fosters end-to-end, direct, and comprehensive collaboration between university faculty and government agencies. It supports innovative DA research, prepares the next-generation DA workforce, and facilitates the transition of DA research to operational applications. CADRE performs a broad scope of cutting-edge research to address multiscale, nonlinear, and coupled Earth system DA challenges to improve short-range (subhourly) to seasonal predictions. It achieves this task through innovative data assimilation algorithm development, novel applications of machine learning (ML) in DA, and optimizing the utilization of existing and new in situ and remotely sensed observations. Beyond research, CADRE establishes a comprehensive education, workforce development, and community building program, which includes a novel graduate student advising model, new university class curriculum development, public training courses, community scientific workshops, an international exchange program, transdisciplinary partnerships, an outreach program, and promotion of the open sharing of data, code, and educational materials. Through this unique holistic approach, CADRE is set to strengthen both the intellectual and software infrastructure in the broad community for DA research, increase the number of DA scientists with expanded skill sets, and revolutionize forecasting capabilities.

*Significance Statement:* Data assimilation is a transdisciplinary science field that plays a significant role in daily weather forecasting. This article introduces the Consortium for Advanced Data Assimilation Research and Education (CADRE), a university-led new initiative that addresses the scientific, technical, and workforce challenges of this field through a holistic approach. Early research efforts of CADRE demonstrate the potential of scientific innovation of data assimilation in transforming high-impact weather predictions. Early workforce development success of CADRE further reveals the need for such an initiative in systematically facilitating the building of the community to address the serious shortage of talent in this field. These findings suggest the natural next step is to expand CADRE.

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