Multi-scale Arctic prediction with MPAS-CESM

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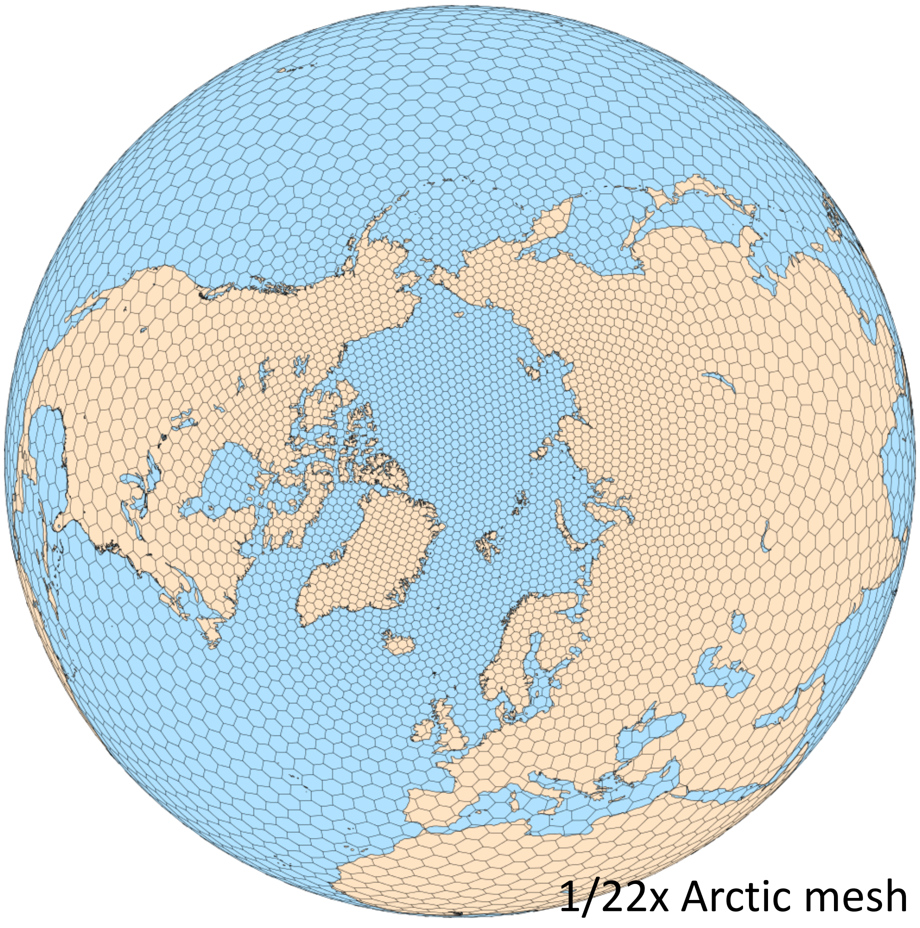
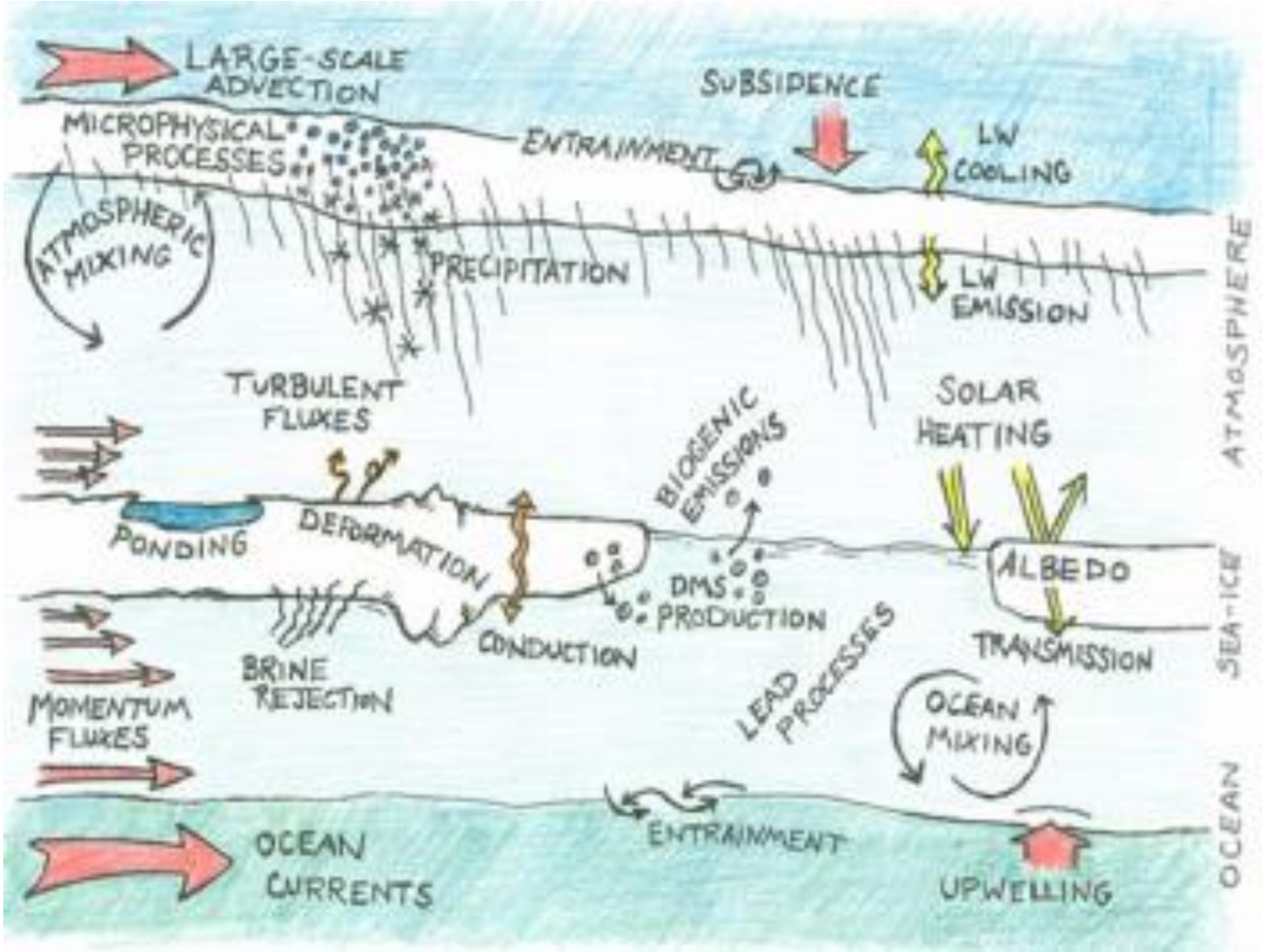


CESM Workshop 2017
PCWG
Boulder, CO
2017-06-21

Grateful for support from
ONR, NCAR MPAS-A group, & CISL

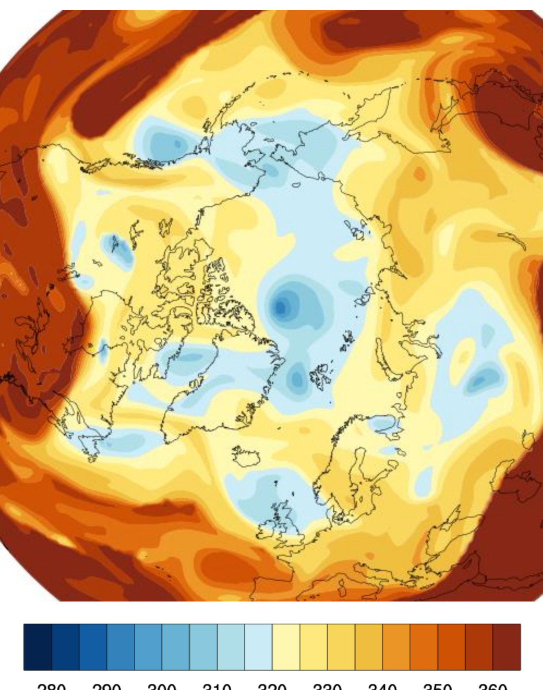
Mass, momentum, & energy deeply coupled across boundary layer, latitudes, & strat-trop

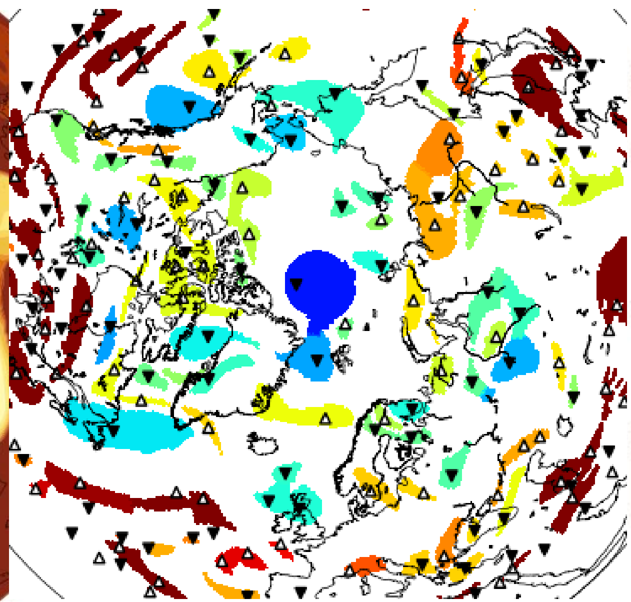


MOSAiC Science Plan

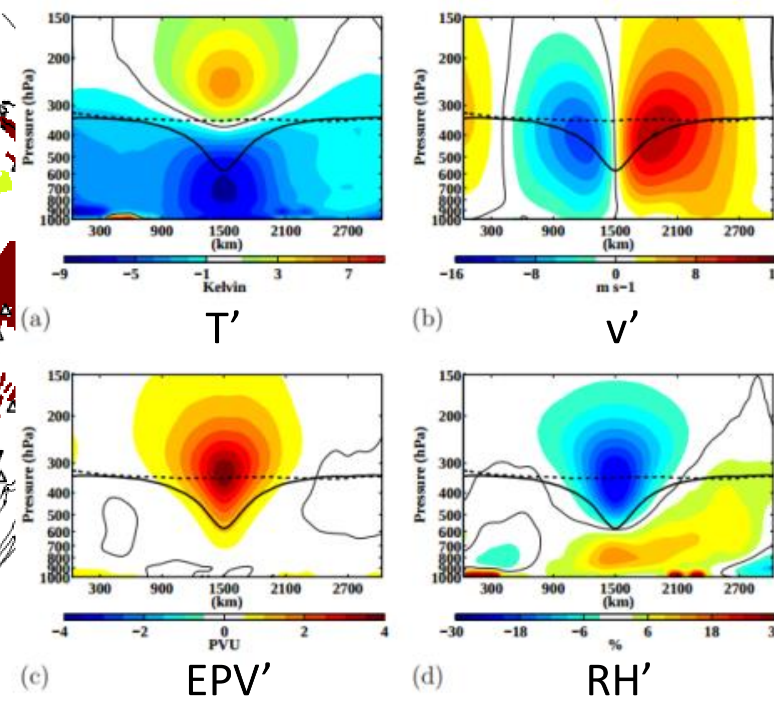
Tropopause Polar Vortices

- Consider potential temperature on 2 PVU tropopause [e.g., Morgan & Nielsen-Gammon, 1998; Ivanova, 2013]
- TPVs are spatially and temporally coherent vortices O(100s-1000 km, 1-40 K, days-months) [Hakim & Canavan, 2005; Cavallo & Hakim, 2009]





TPVTrack segmentation



Upper level potential vorticity anomalies in synoptic "IPV thinking"

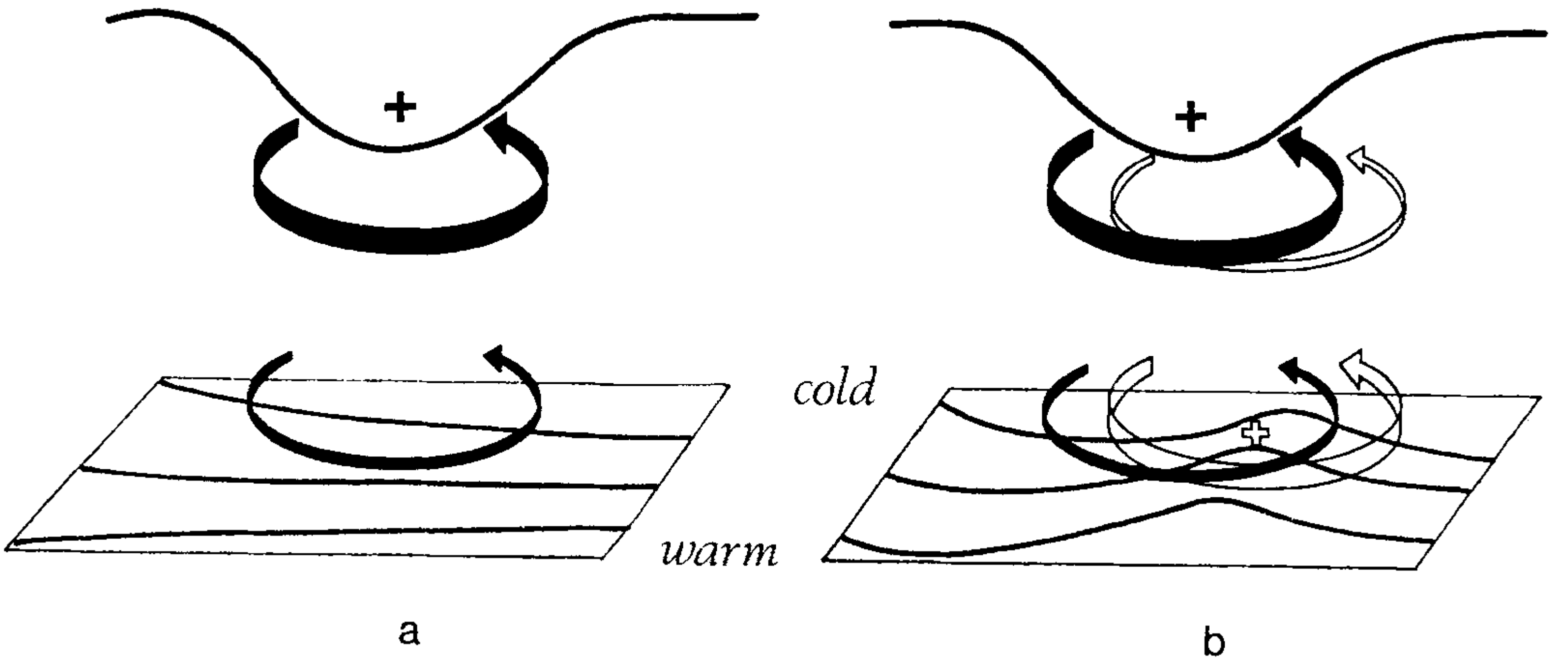
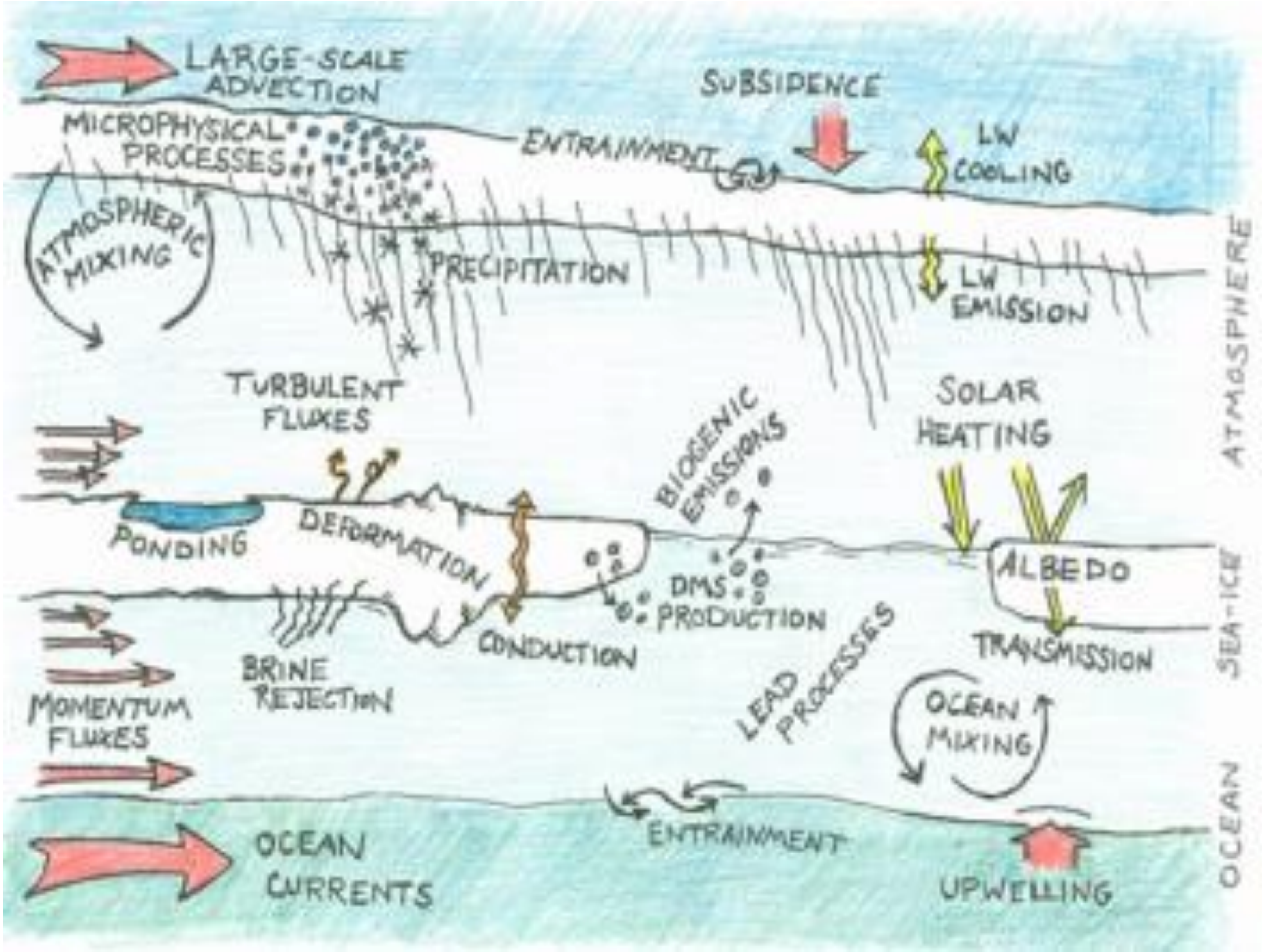


Figure 21. A schematic picture of cyclogenesis associated with the arrival of an upper air IPV anomaly over a low-level baroclinic region. In (a) the upper air cyclonic IPV anomaly, indicated by a solid plus sign and associated with the low tropopause shown, has just arrived over a region of significant low-level baroclinicity. The circulation induced by the anomaly is indicated by solid arrows, and potential temperature contours are shown on the ground. The low-level circulation is shown above the ground for clarity. The advection by this circulation leads to a warm temperature anomaly somewhat ahead of the upper IPV anomaly as indicated in (b), and marked with an open plus sign. This warm anomaly induces the cyclonic circulation indicated by the open arrows in (b). If the equatorward motion at upper levels advects high-PV polar lower-stratospheric air, and the poleward motion advects low-PV subtropical upper-tropospheric air, then the action of the upper-level circulation induced by the surface potential temperature anomaly will, in effect, reinforce the upper air IPV anomaly and slow down its eastward progression. (To this extent the situation is similar to the small-amplitude instability situation represented by Fig. 18 and described in section 6(*b*).)

Hoskins et al. 1985

With a spectrum of scales w/in each component:
How does model design impact processes?
How do filters impact evolution, variability, & prediction?



MOSAiC Science Plan

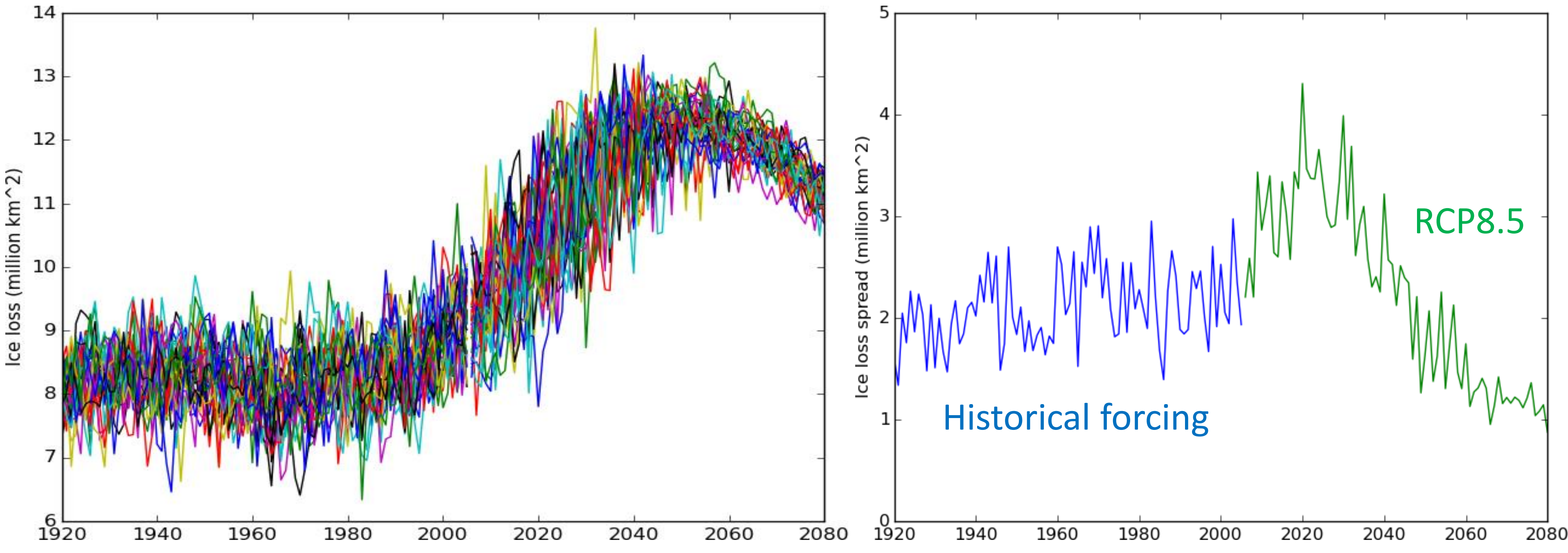
Setup of CESM Large Ensemble [Kay et al. 2015]

	1850 fully coupled control	1850 atmosphere and land control	Ensemble member 1	Ensemble member 2–*N*
Case name[a]	b.e11.B1850C5CN.f09_g16.005	f.e11.F1850C5CN.f09_f09.001	b.e11.B20TRC5CNBDRD.f09_g16.001, b.e11.BRCP85C5CNBDRD.f09_g16.001	b.e11.B20TRC5CNBDRD.f09_g16.00N, b.e11.BRCP85C5CNBDRD.f09_g16.00N
Years[b]	1,500 years, years 400–1500 released	2,000 years, years 1–1999 released	1850–2100	1920–2100
Prognostic model components	Atmosphere, ocean, land, sea ice	Atmosphere, land	Atmosphere, ocean, land, sea ice	Atmosphere, ocean, land, sea ice
Forcing	Preindustrial (1850), Whole Atmosphere Community Climate Model (WACCM) ozone forcing[c]	Preindustrial (1850) with prescribed monthly mean sea surface temperature and sea ice averaged over years 402–1510 of the 1850 control, WACCM ozone forcing[c]	1850–2005 historical, 2006–2100 RCP8.5 well-mixed greenhouse gases (Meinshausen et al. 2011) and short-lived gases and aerosols (Lamarque et al. 2011), WACCM ozone forcing[c]	Same as ensemble member 1 for overlapping years
Initialization	Jan mean present-day potential temperature and salinity from PHC2 dataset for ocean, previous CESM1(CAM5) 1850 control run for atmosphere, land, and sea ice	1 Jan, year 402 of 1850 coupled control for atmosphere and land. For ocean/ice, N/A.	1 Jan, year 402 of 1850 coupled control for all model components (atmosphere, land, ocean, sea ice)	Ensemble member 2: 1 Jan 1920 of ensemble member 1 started with 1-day lagged ocean temperatures Ensemble members 3–*N*: 1 Jan 1920 of ensemble member 1 for all model components; atmosphere with round-off (order of 10^{-14} K) differences in air temperature

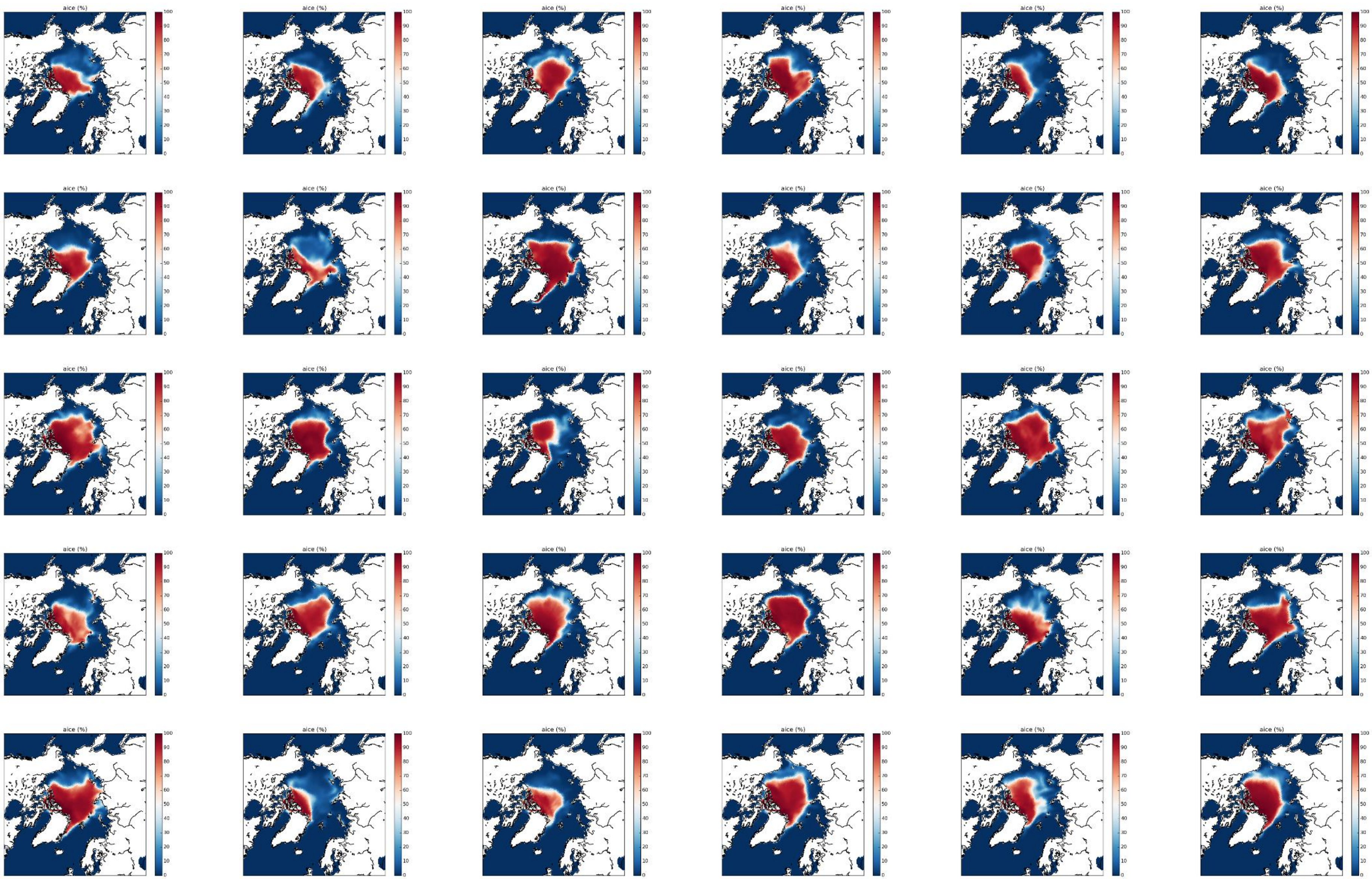
Forced+internal variability in CESM-LE

- Greater sensitivity of thinner, younger ice [Maslanik et al. 2007; Kwok et al. 2013]
  - With rapid ice loss events from anthro. forcing+growing intrinsic variability [Holland et al. 2008]

March-September Arctic sea ice area
from 30 members of CESM-LE [Kay et al. 2015]



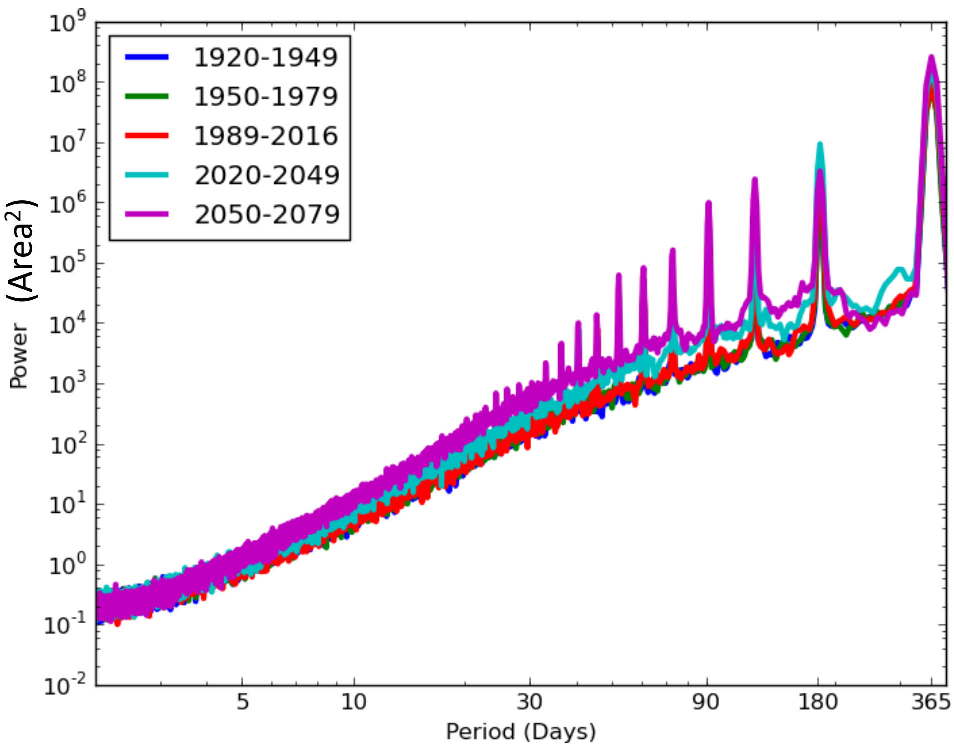
Sensible internal variability in CESM-LE: aice in 2021-09



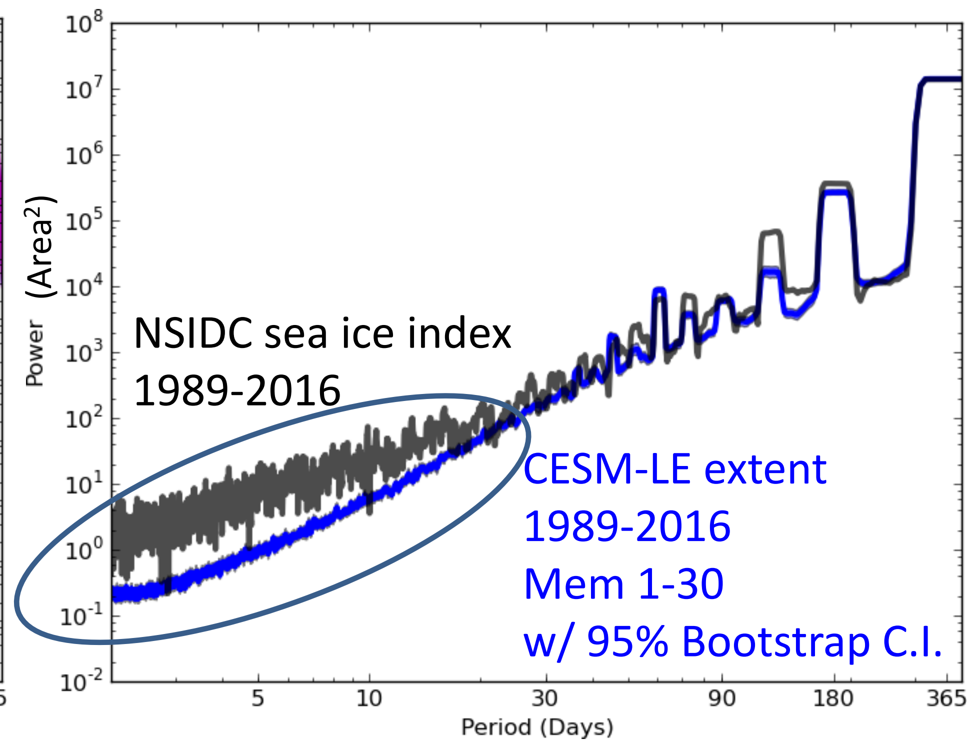
Scales in CESM-LE: Power spectra of daily sea ice extent

FFT-based power spectrum:

1. Daily SIE from aice .ge. 15%
2. Blackman taper
3. Mean PSD across members 1-30

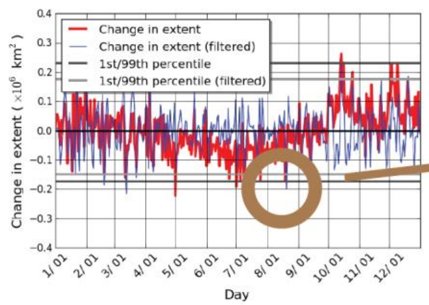


PSD smoothed w/ +/- 5 sample mean

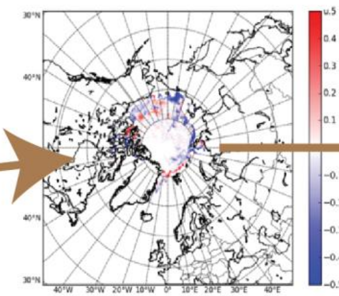


What drives rapid ice loss?
Compositing procedure for synoptic events

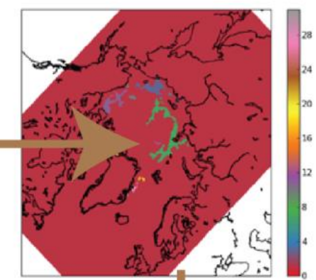
(1) Identify event



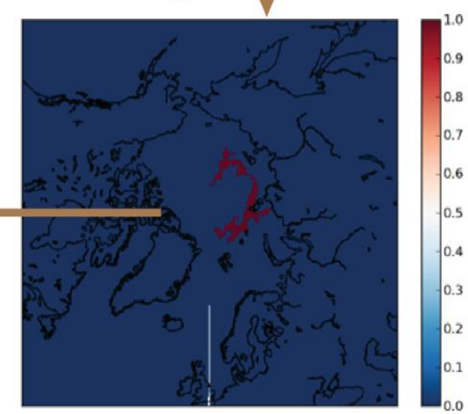
(2) Calculate Δconcentration



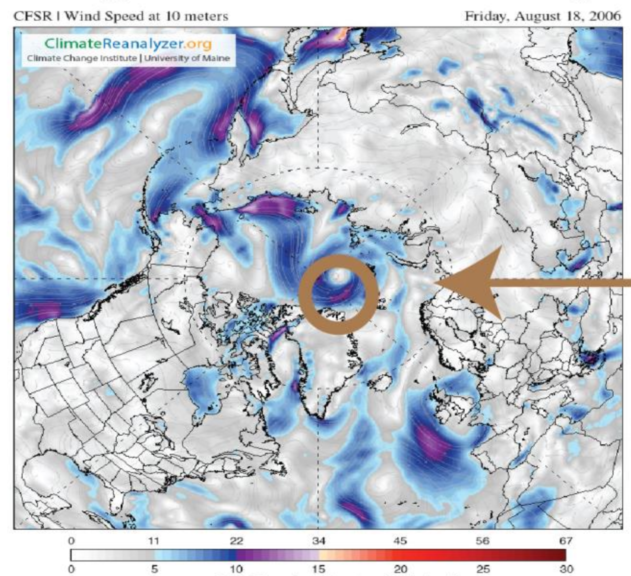
(3) Separate into objects



(4) Find object with largest Δextent



(5) Reference location = grid point with greatest 10-m wind speed on object

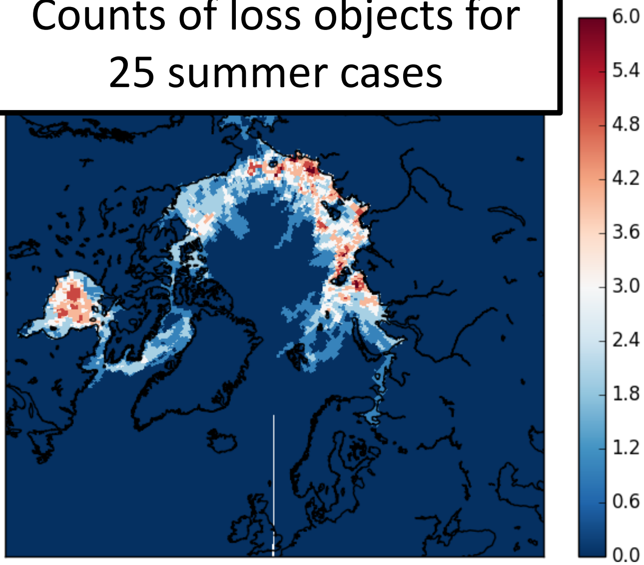


18d High-pass pan-Arctic SIE
NSIDC concentration
ERA-Interim

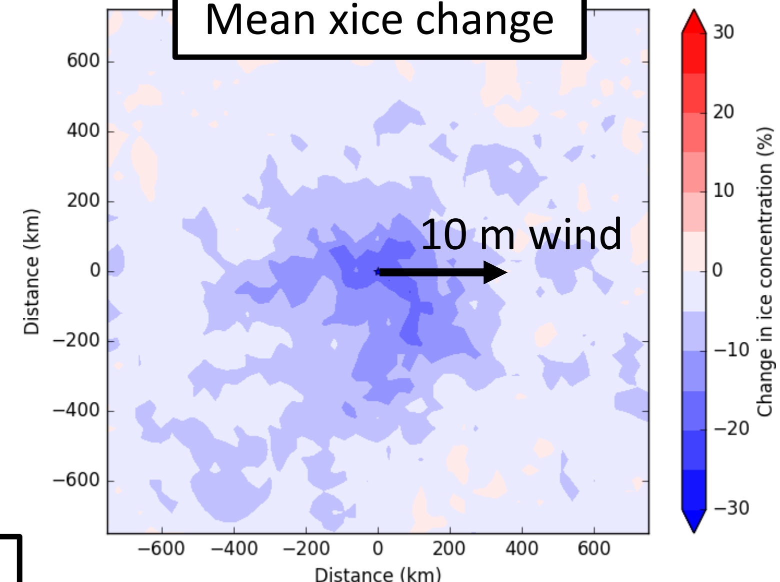
Initially REU project w/ Uriel Gutierrez

Top 1% Synoptic Rapid Ice Loss Events: Associated w/ surface lows + TPVs

Counts of loss objects for 25 summer cases

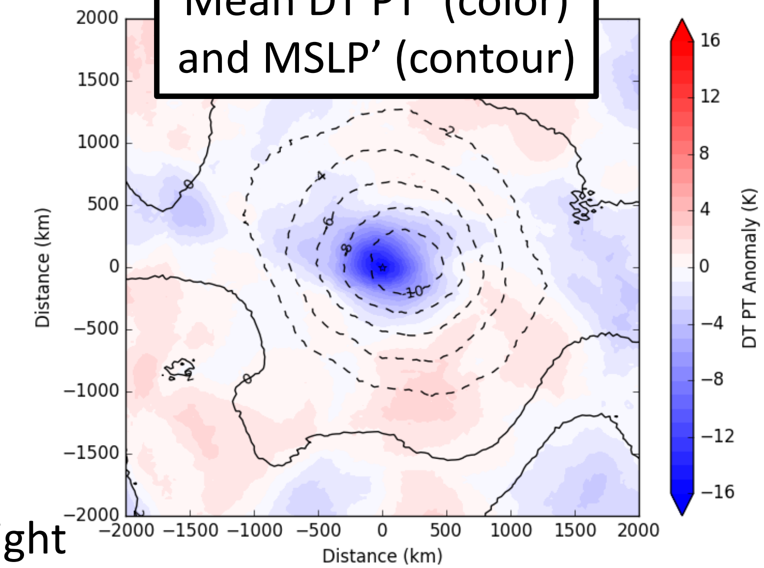


Mean xice change



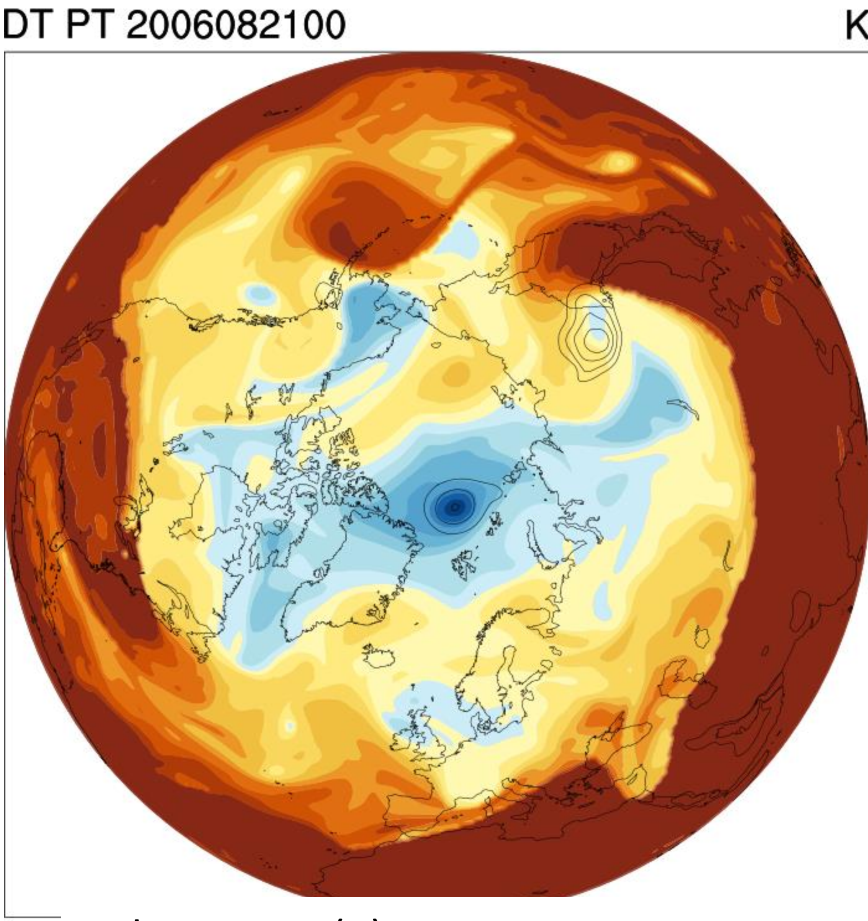
Composite mean in local reference frame w/ 10 m wind flowing to the right

Mean DT PT’ (color) and MSLP’ (contour)

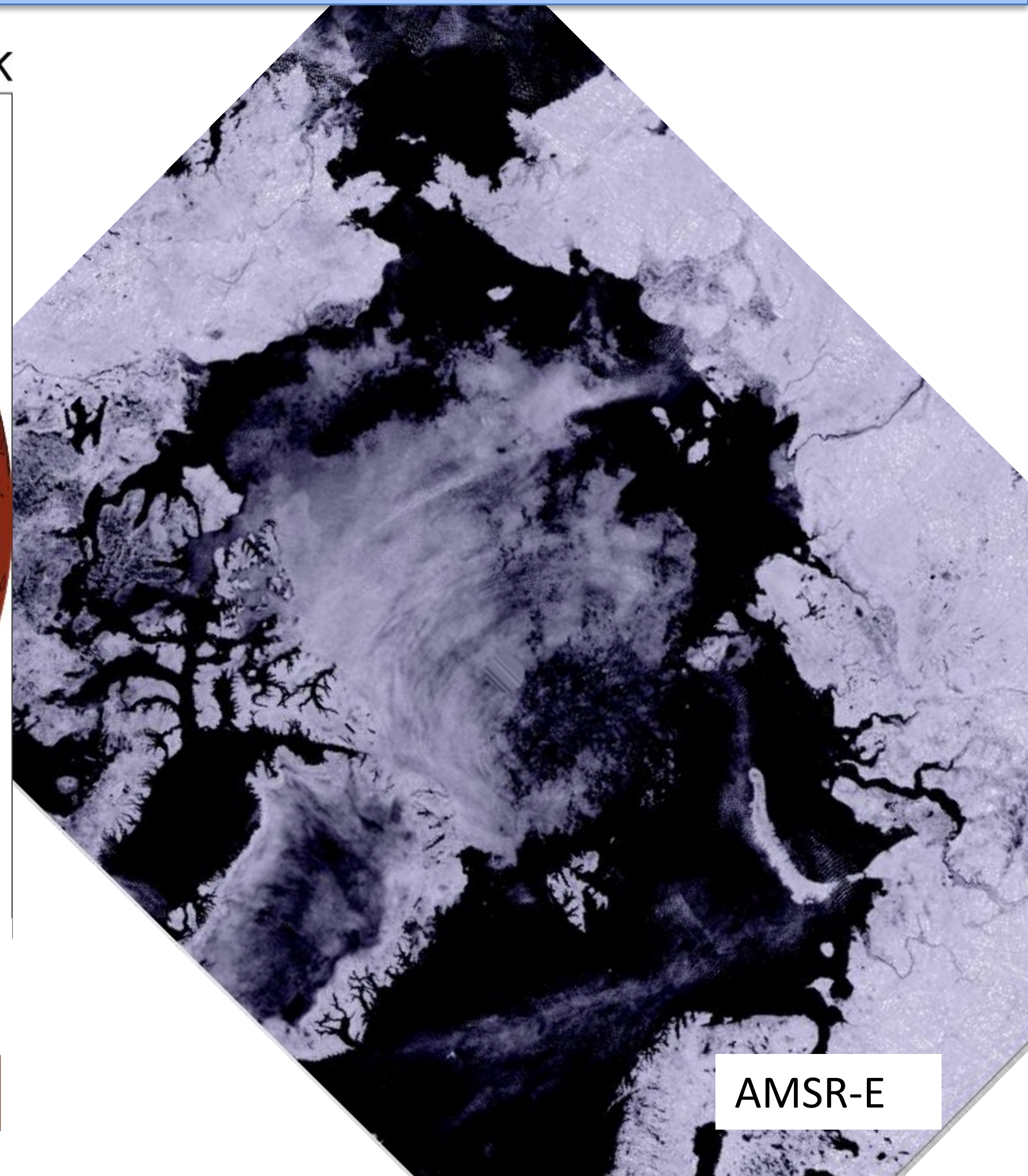


Composite mean in local reference frame centered on TPV core w/ MSLP min to the right

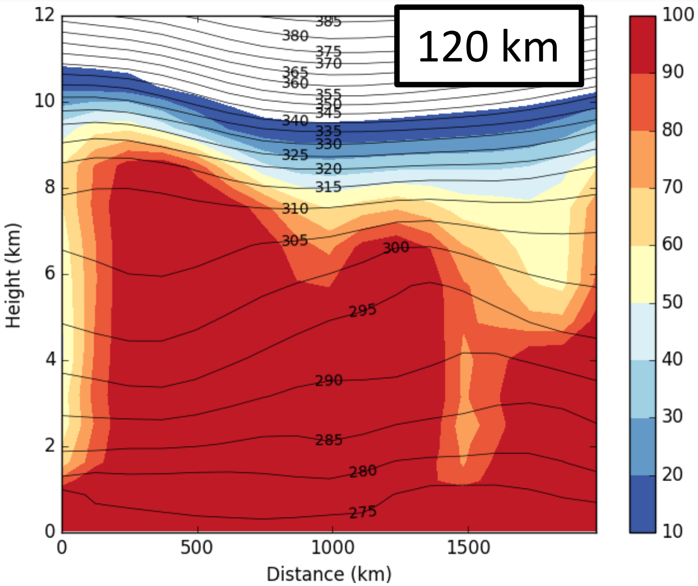
August 2006 SRILE

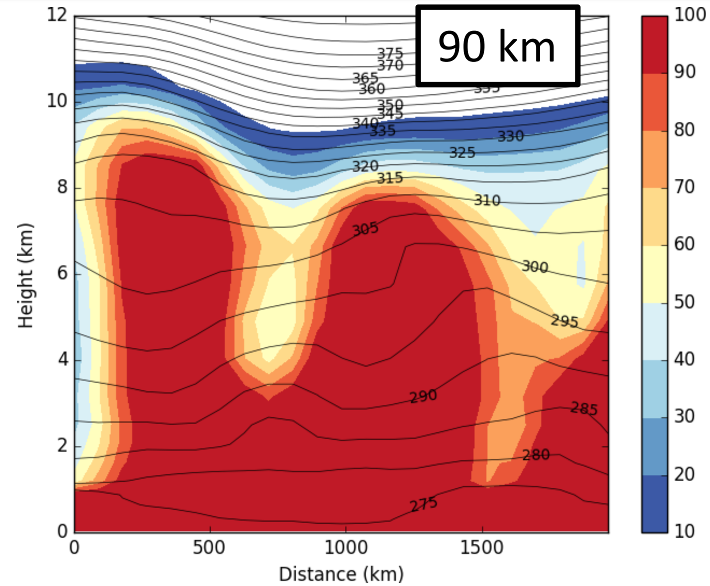


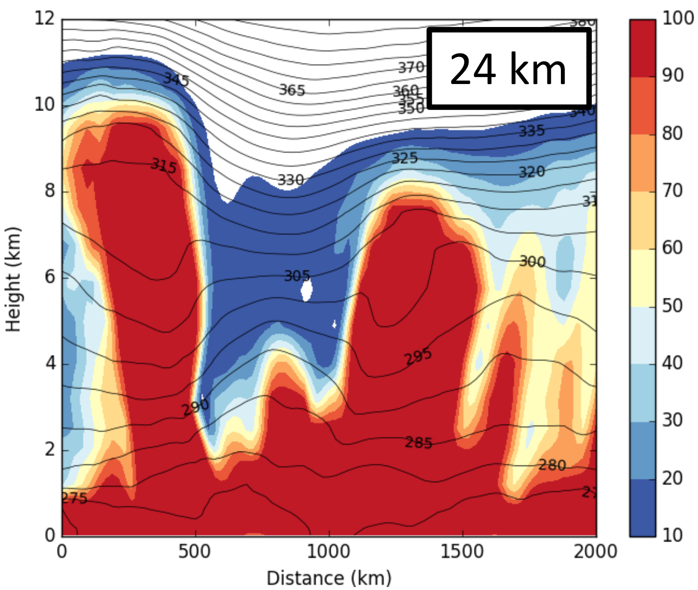
Color: DT PT (K)
Contour: MSLP .lt. 1000 hPa (Δ=4 hPa)

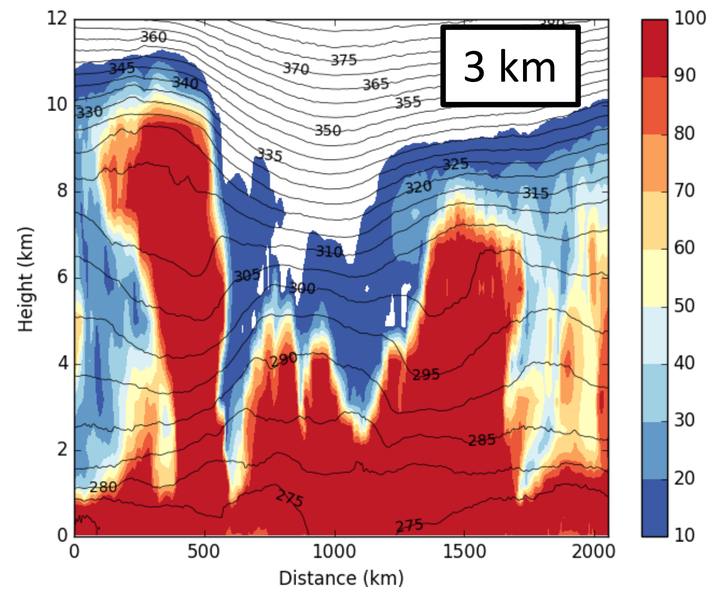


TPV-surface cyclone in WRF-ARW: Sensitivity to grid scale









Color: RH (%)
Contour: PT (K)

Simulations:
Chris Riedel

Polar filter affects TPV dynamics

- Increased damping of (Fourier) zonal wavenumbers towards pole for increased stability

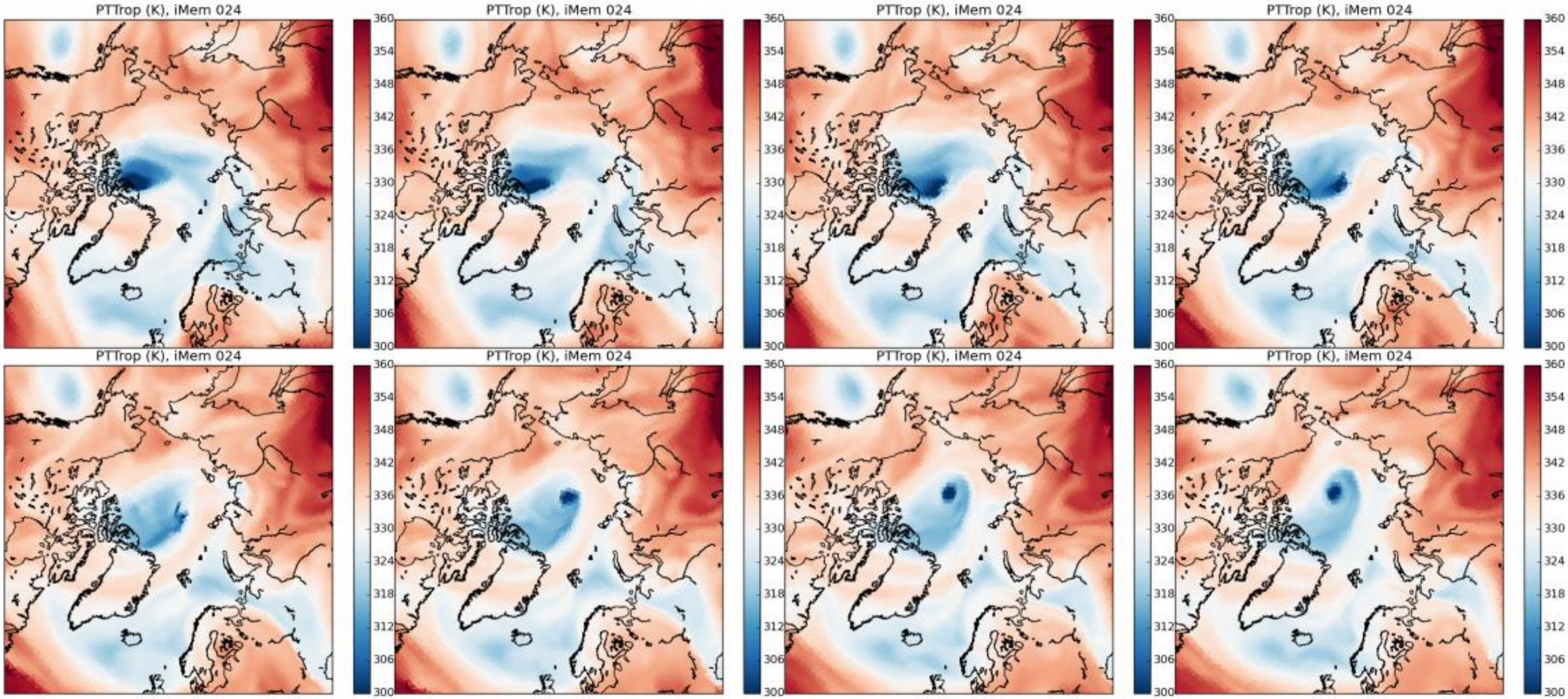


Figure 2: Six hourly tropopause potential temperature for CESM-LE member 24 in July 2034 for the ninth (top) and tenth (bottom). Note the odd evolution as the TPV crosses the pole (bottom left).

Overview of Model for Prediction Across Scales (MPAS-A)

Fully Compressible Nonhydrostatic Equations

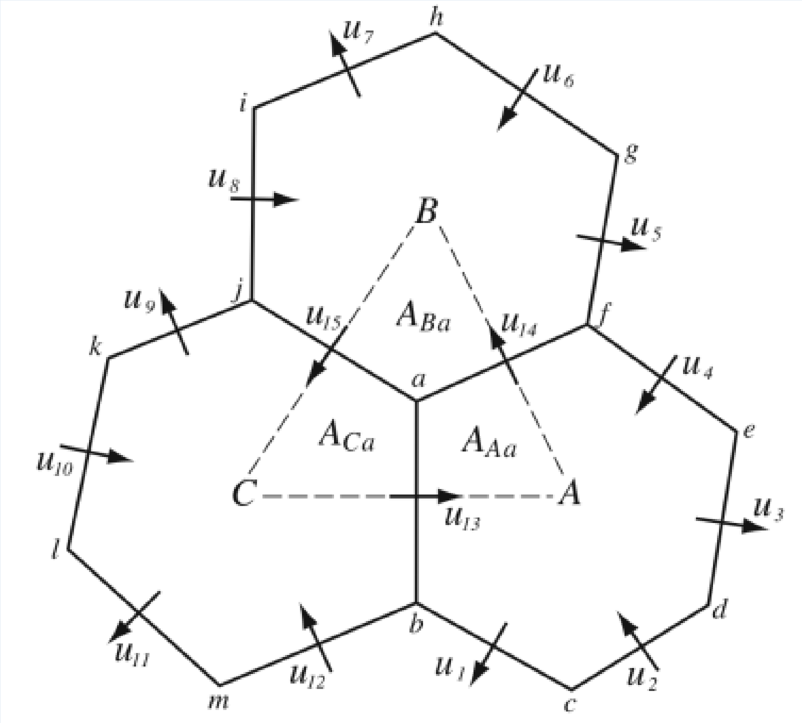
- Prognostic equations for coupled variables.
- Generalized height coordinate.
- Horizontally vector invariant eqn set.
- Continuity equation for dry air mass.
- Thermodynamic equation for coupled potential temperature.

Time integration as in Advanced Research WRF

- Split-explicit Runge-Kutta (3rd order)

Full complement of atmospheric-model physics

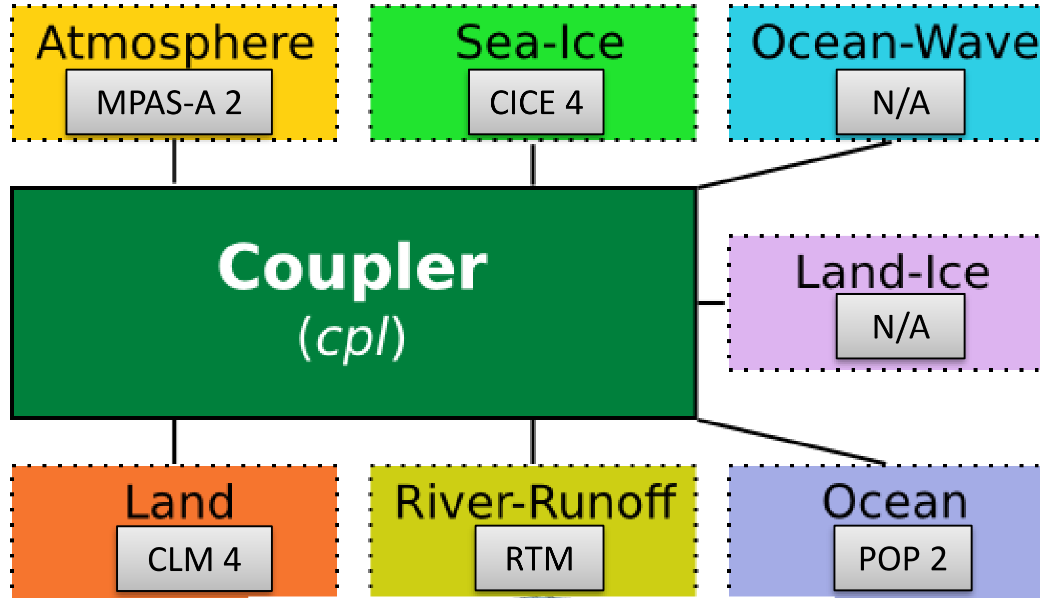
MPAS is based on unstructured centroidal Voronoi (hexagonal) meshes using C-grid staggering and selective grid refinement.

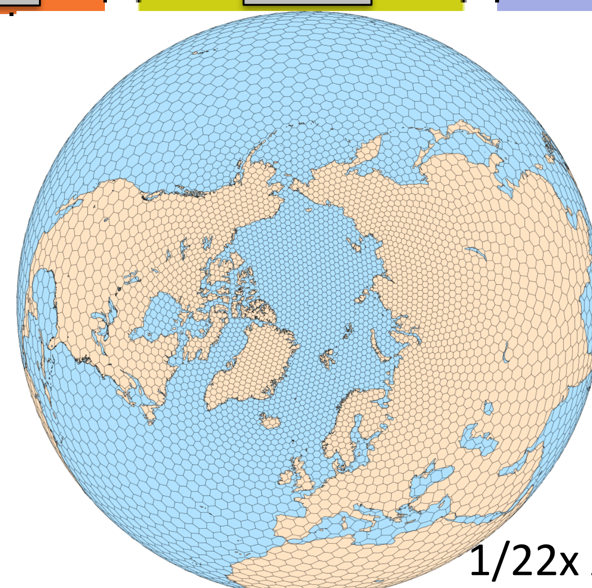


MPAS-A Tutorial (http://www2.mmm.ucar.edu/projects/mpas/tutorial/UK2015/slides/MPAS-overview.pdf)

MPAS-CESM 1.4.b7 (v2.0.b5 in testing) Dynamical, global, coupled, var-res (atmo)

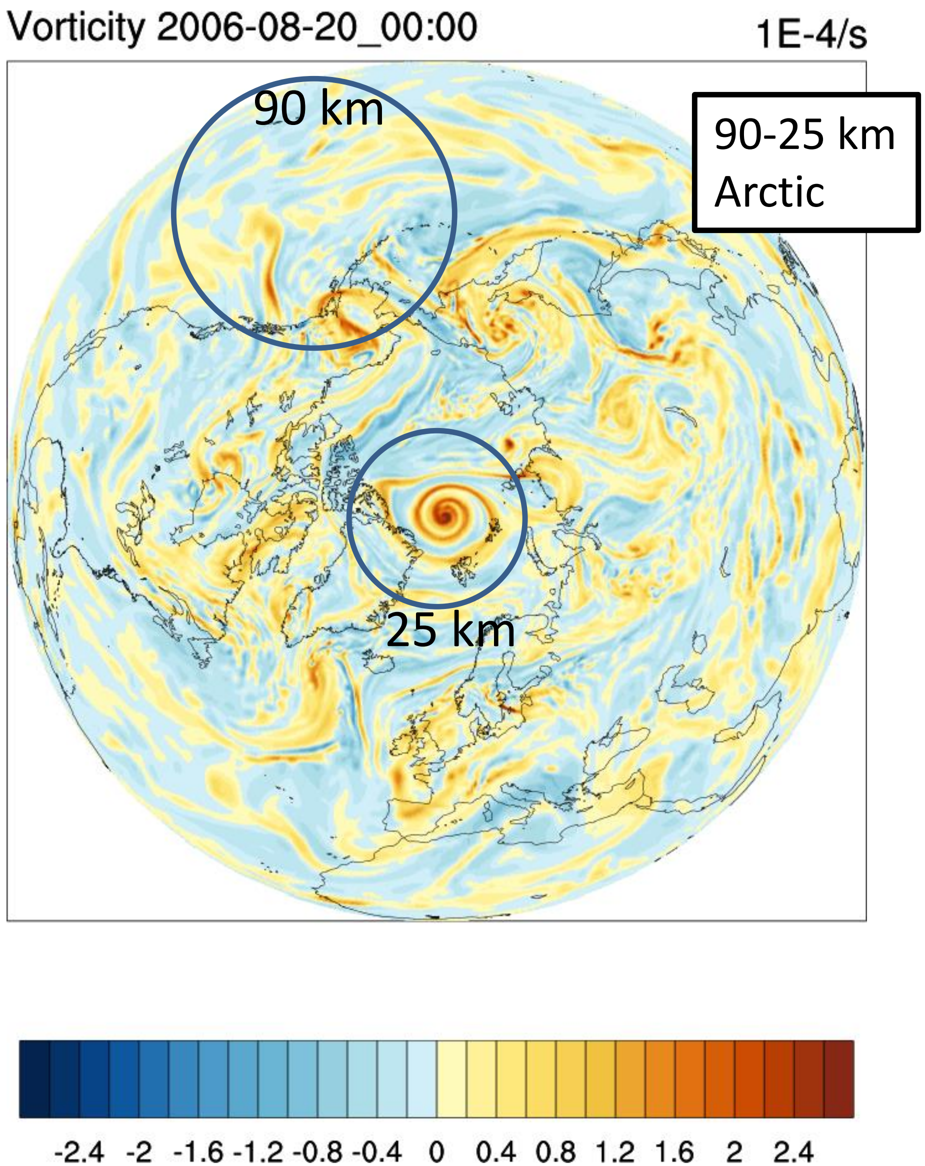
- Atmosphere: CAM5.3 with MPAS-A dycore
  - Physics: 30min dt w/ dribbled tendencies
  - Vertical levels as in CAM5: 30 levels to 44.6km
- Land: CLM4 on ~1° FV grid
  - 30 min coupling to atm
- Ocean: POP2 on ~1° Greenland tri-pole
  - 1 day coupling to atm
- Sea ice: CICE4 on ~1° Greenland tri-pole
  - 30 min coupling to atm
- River: RTM
  - 3 hr coupling
- Coupling: CPL7 w/ atm←→* fluxes on atm grid
- Cost w/o optimization: ~1000 compute hrs/sim month
- ICs: analysis (atm) and CESM-LE analog (other components)

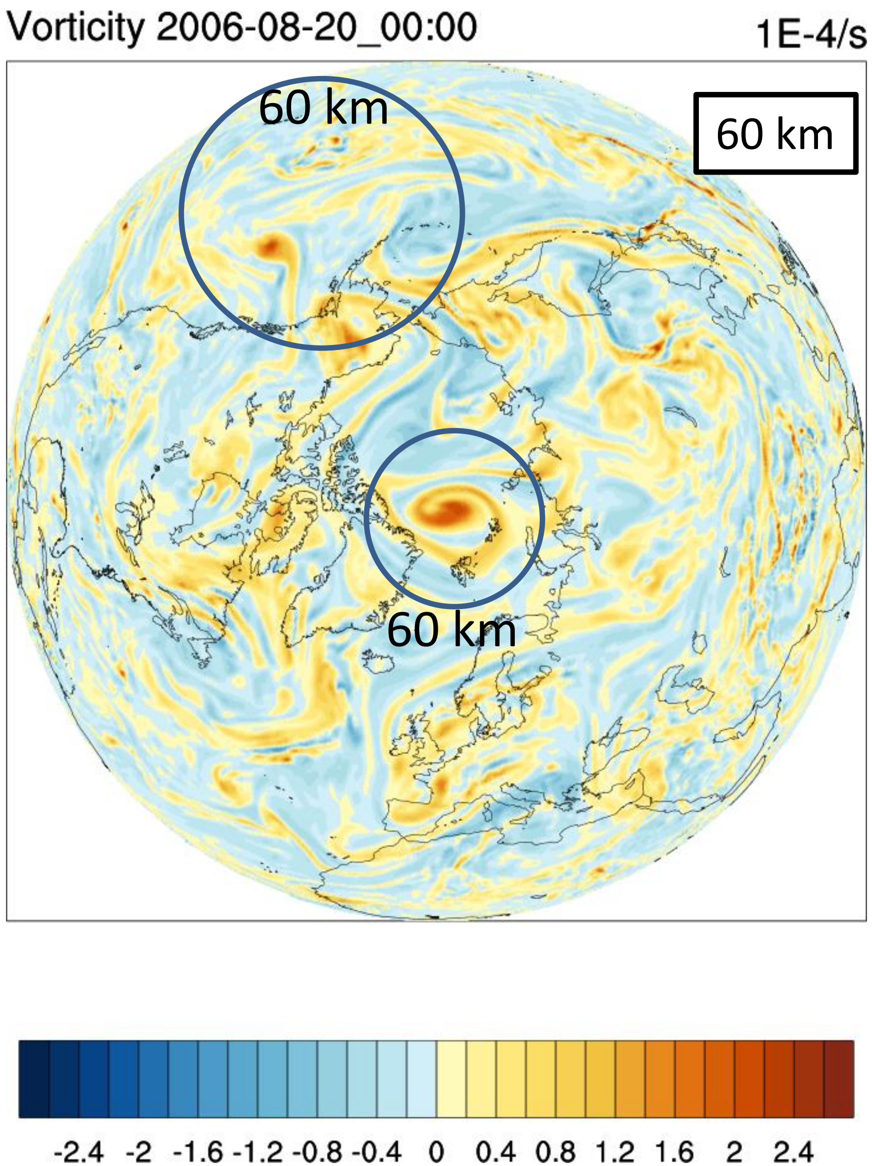




1/22x Arctic mesh

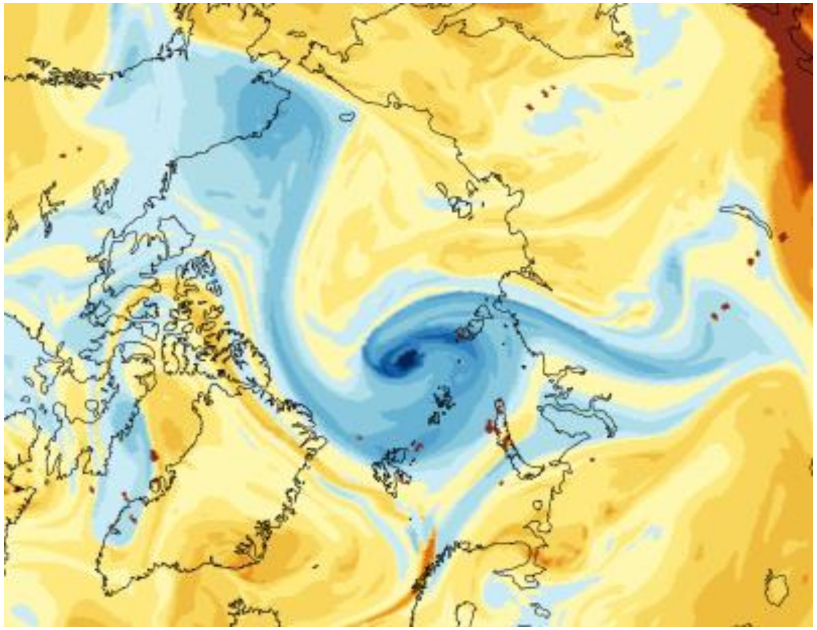
Refinement adds resolution in MPAS-CESM: f120h 500hPa rel. vertical vorticity

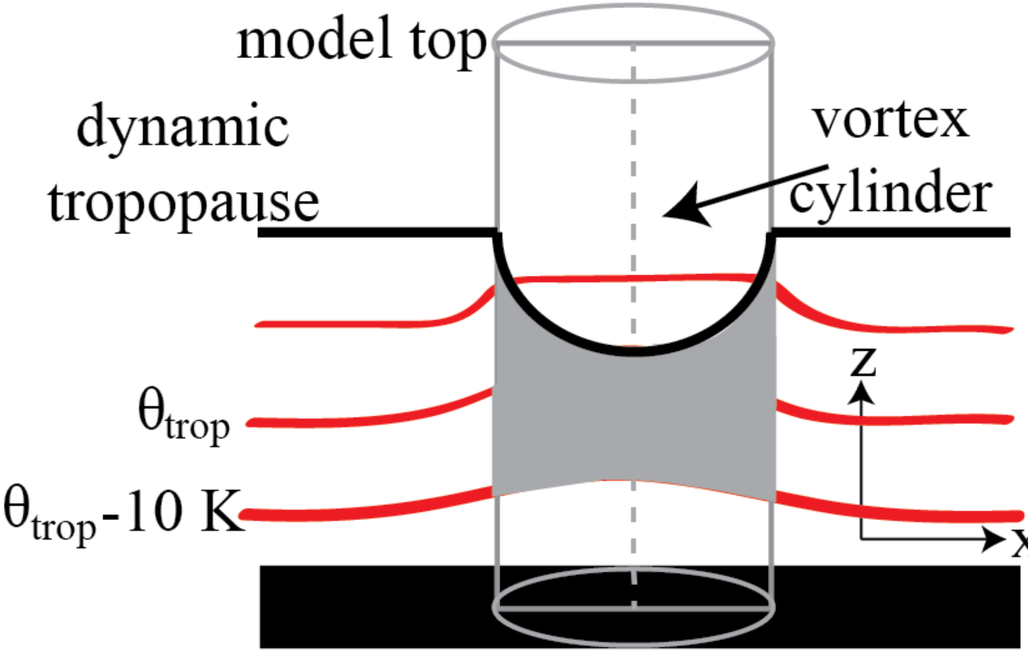




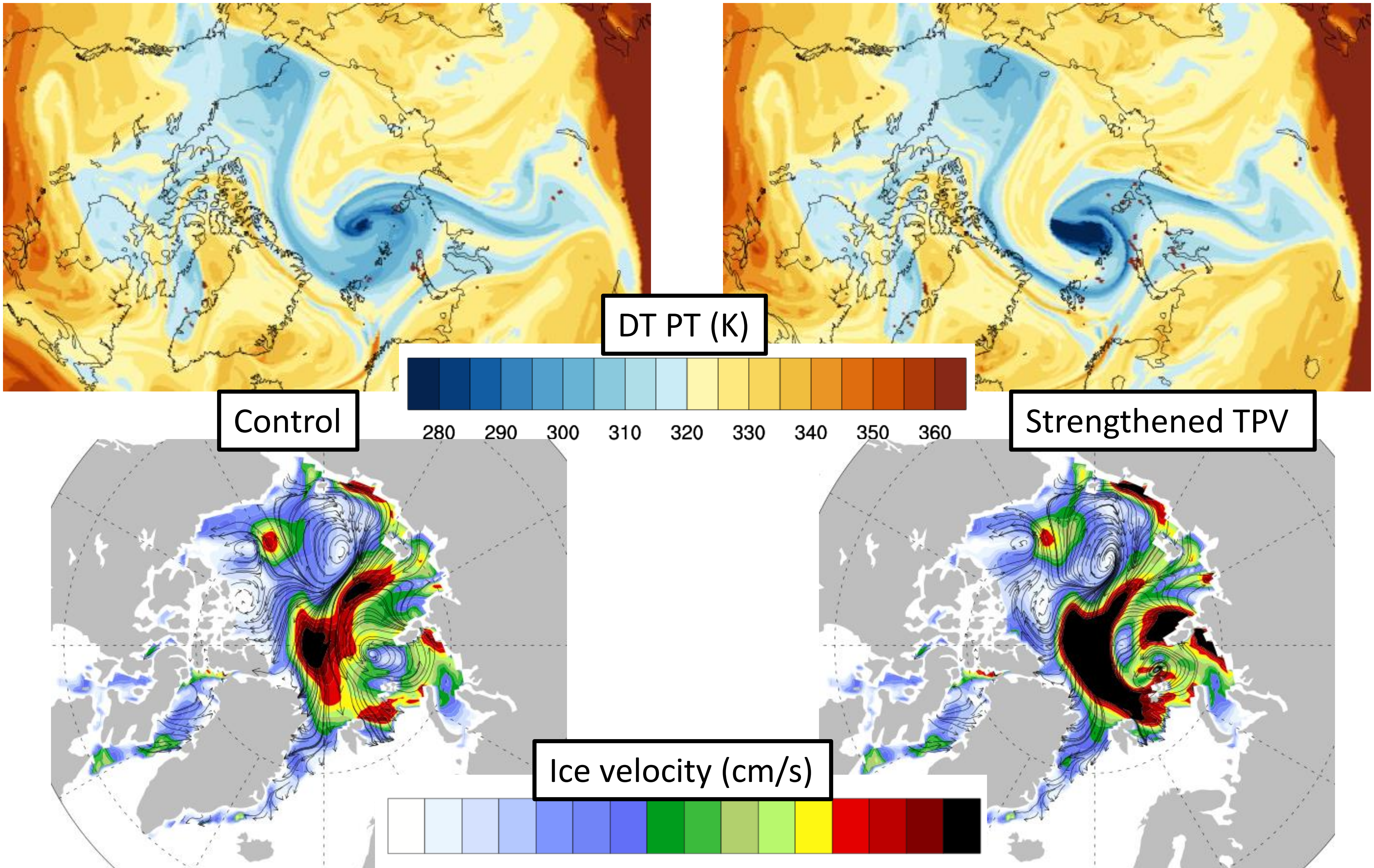
Use sensitivity experiments to quantify impacts of TPV intensity biases

- Localized tendency-based TPV modifications applied throughout integration
  - ID region; e.g., DT PT<300K North of 70N
  - Apply modification; e.g., dθ/dt -= 10K/day [DT-10K,DT)

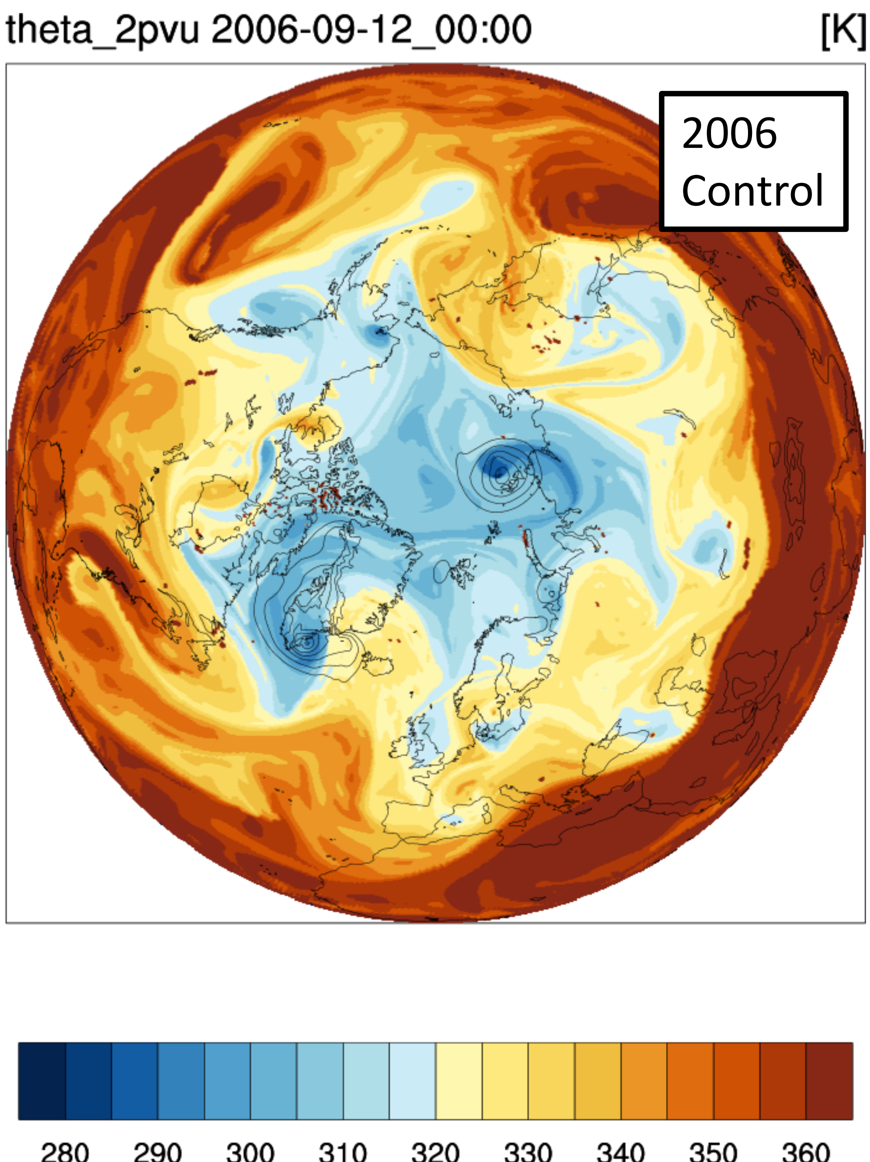


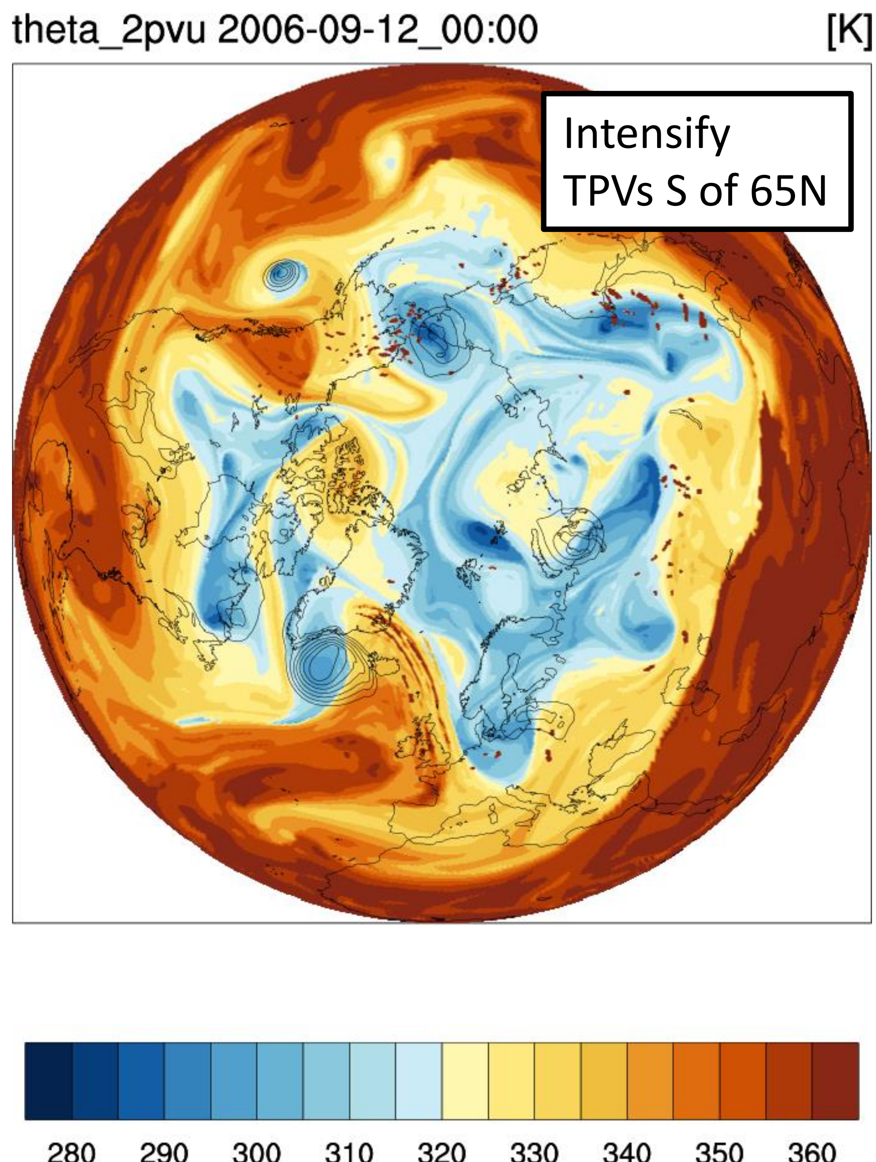


Central Arctic TPVs can impact surface cyclones and sea ice transport: f72h

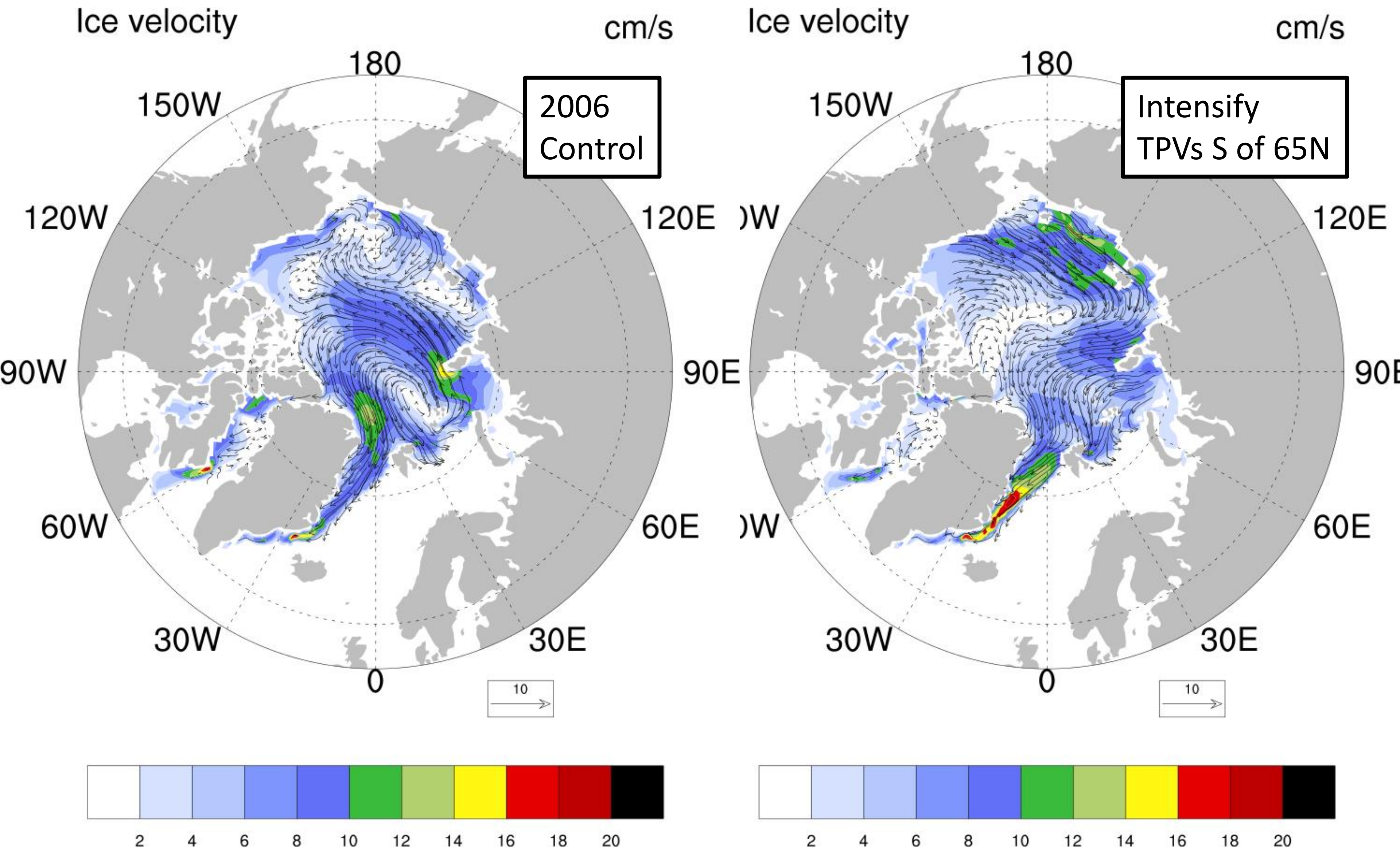


Stronger TPVs at mid-latitudes can amplify waviness: f28d

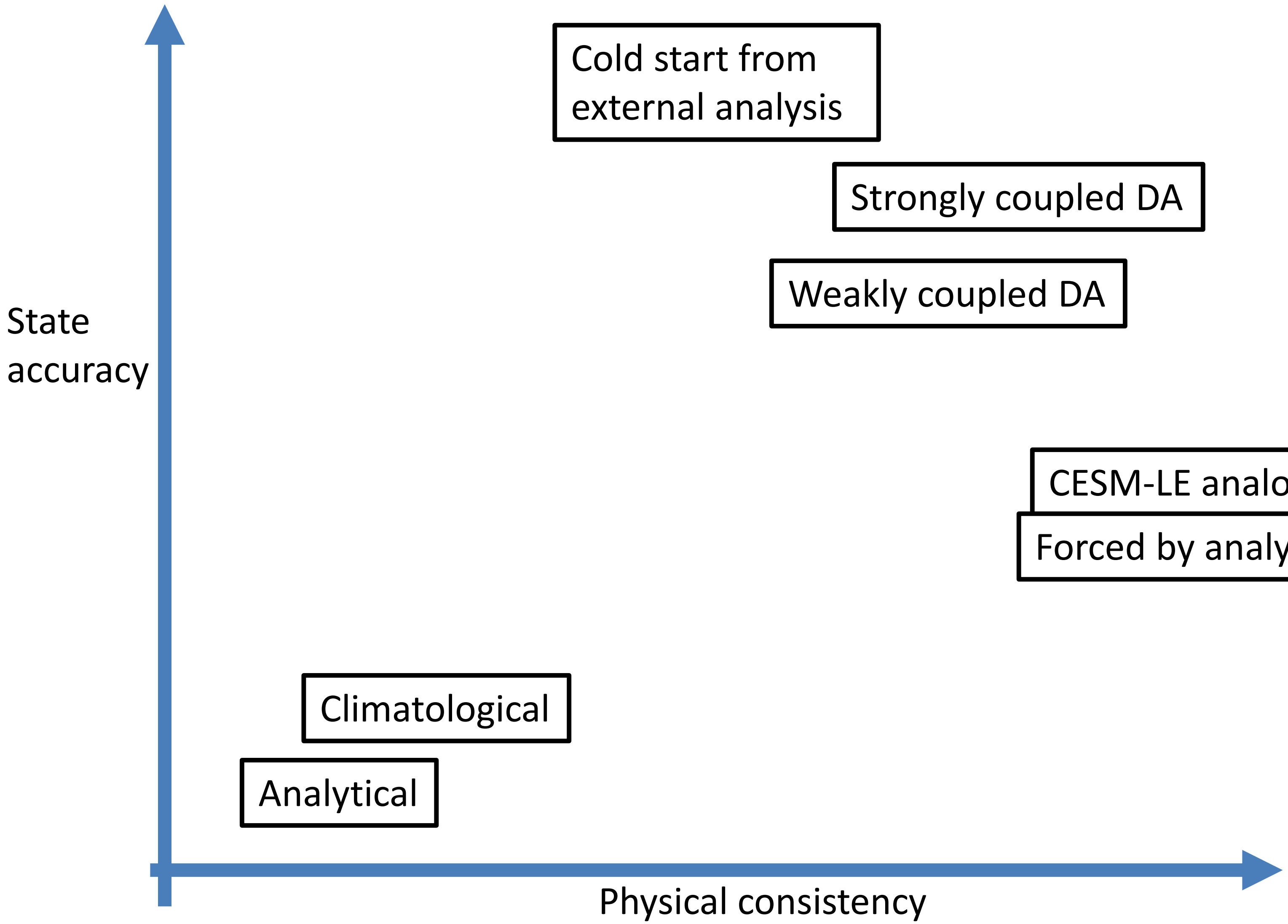




Stronger TPVs at mid-latitudes can impact sea ice motion: time-mean over 28d

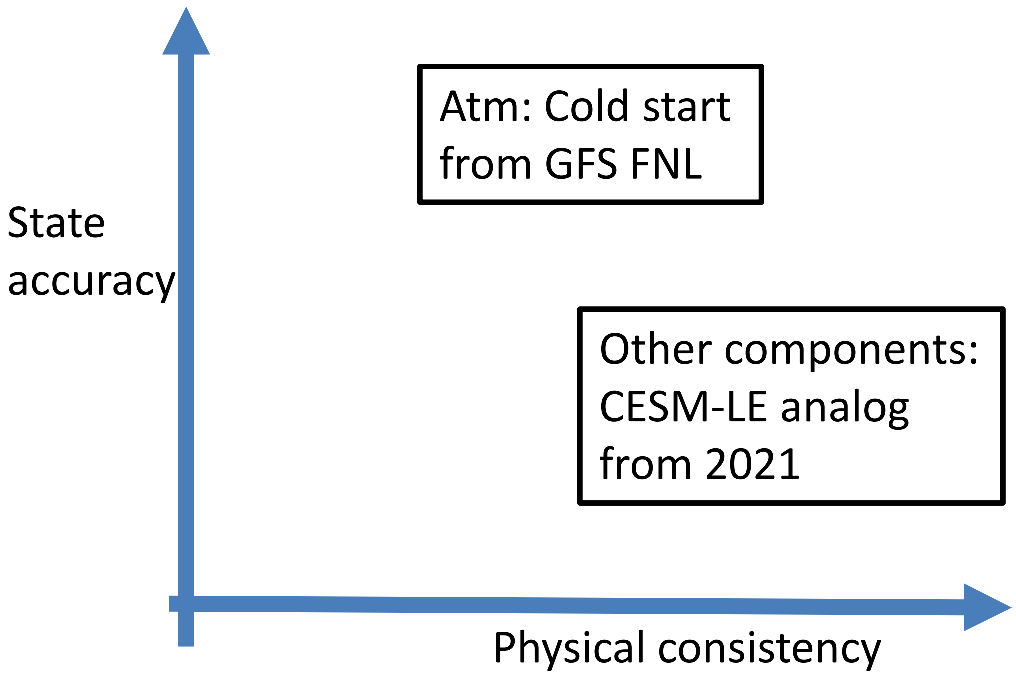


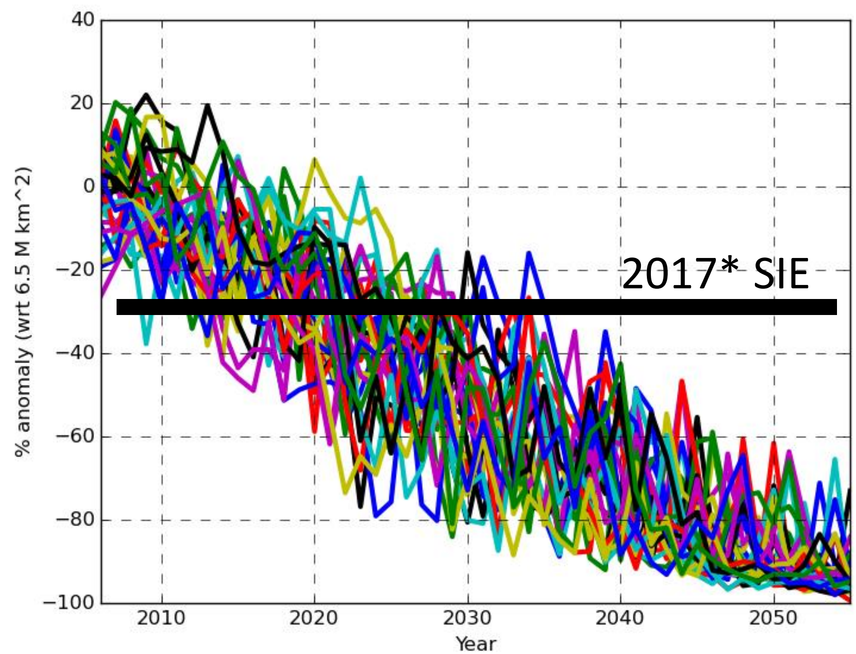
Options for ICs



Initial conditions for 2017 Sea Ice Outlook

- SIO: Collection of June, July, and August 1 forecasts for September mean SIE for Arctic (, Alaska, and Antarctic)

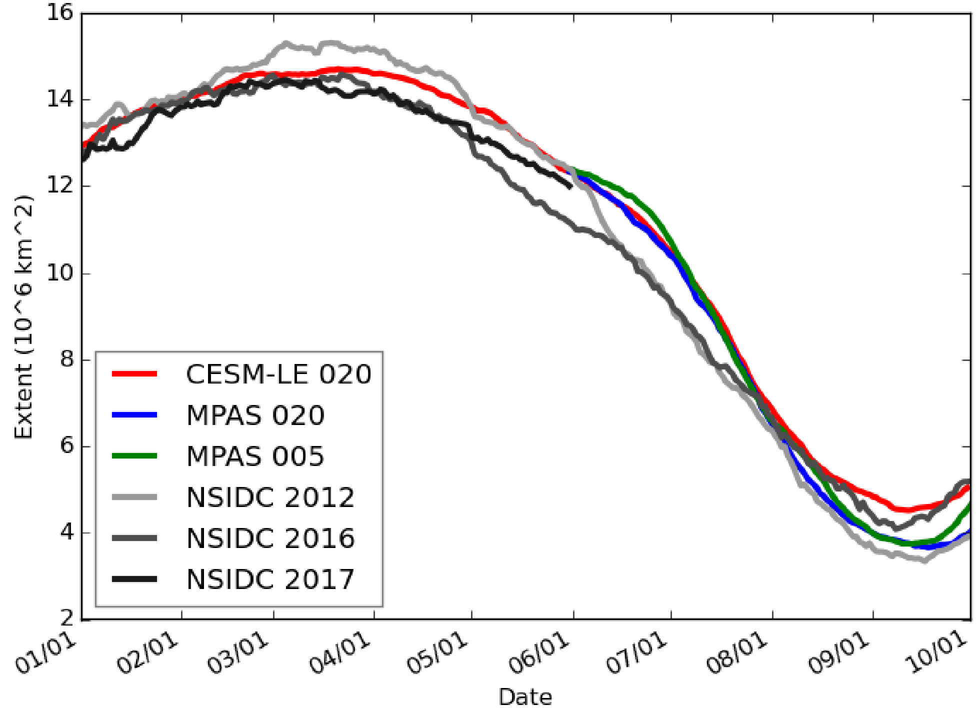




Color: Sep. SIE in CESM-LE by member
*linear extrapolation of Sep. Sea Ice Index

2017 Sea Ice Outlook and summary

- June SIO (M km^2):
  - Arctic: 4.1
  - Alaska: 0.3
  - Antarctic: 18.1



- TPVs can impact surface lows, wave amplification, seasonal circulation, and summer sea ice loss
  - Future: Linearity and dynamics of coupled response to TPV intensity
- MPAS-CESM as a dynamical tool for process and prediction studies
  - Future: Ensemble exploring model design and uncertainty
    - Physics, mesh, numerics, coupling, stochastic physics,…
    - IC uncertainty: GEFS and CESM-LE analogs, ?

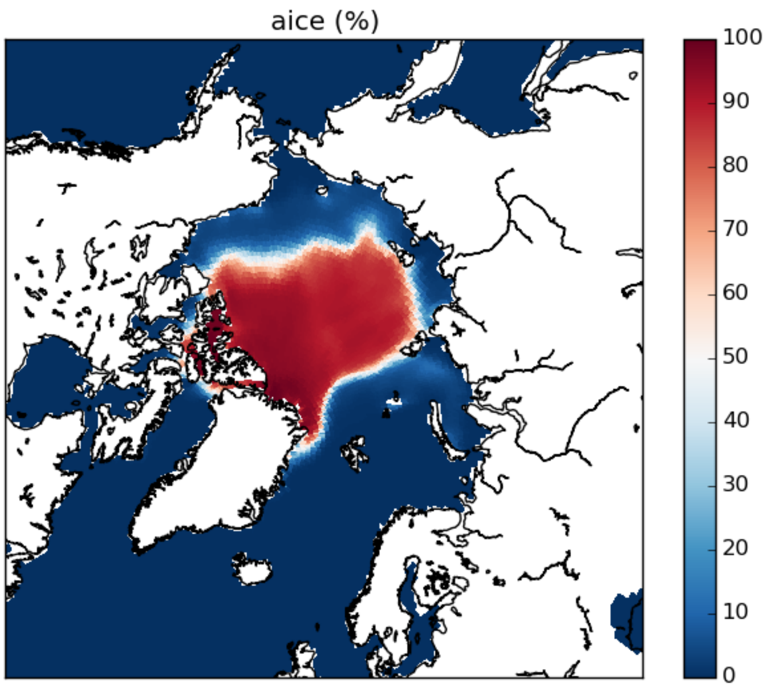
Extra slides

Outline

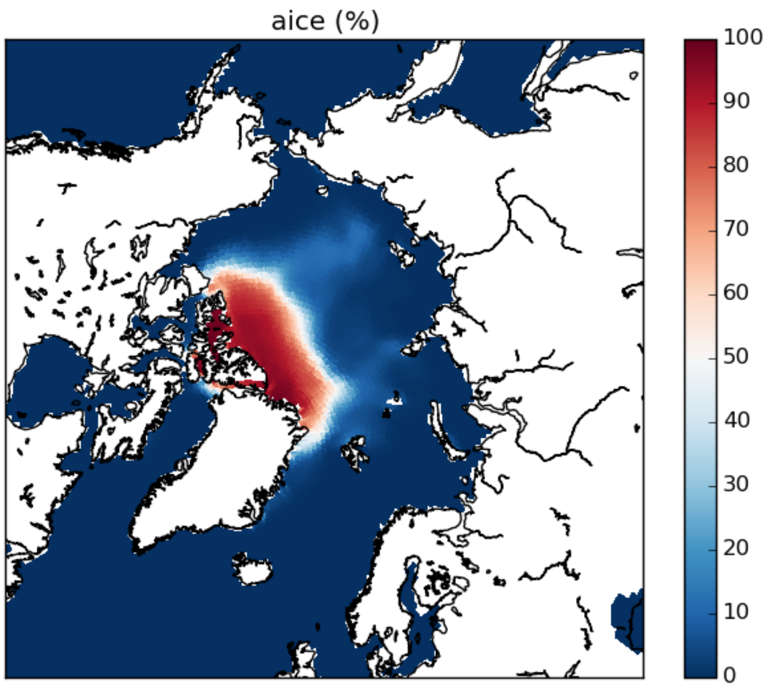
- Background on polar prediction
  - Coupled across BL, strat-trop, latitude
    - Scale filters interactions
  - CESM-LE
    - Forced+natural variability in extent
    - Coarse, polar filter, sea ice spectra
- MPAS-CESM description
  - What is MPAS-A?
  - Setup for MPAS-CESM
- Intrinsic predictability
  - Impacts of weak synoptic features
    - TPV modifications
- Practical predictability
  - Forecast experiments
    - 2017 SIO

Are CESM-LE integrations reproducible? aice for member 005 in 2021-09

Restart from 2021-01



Original

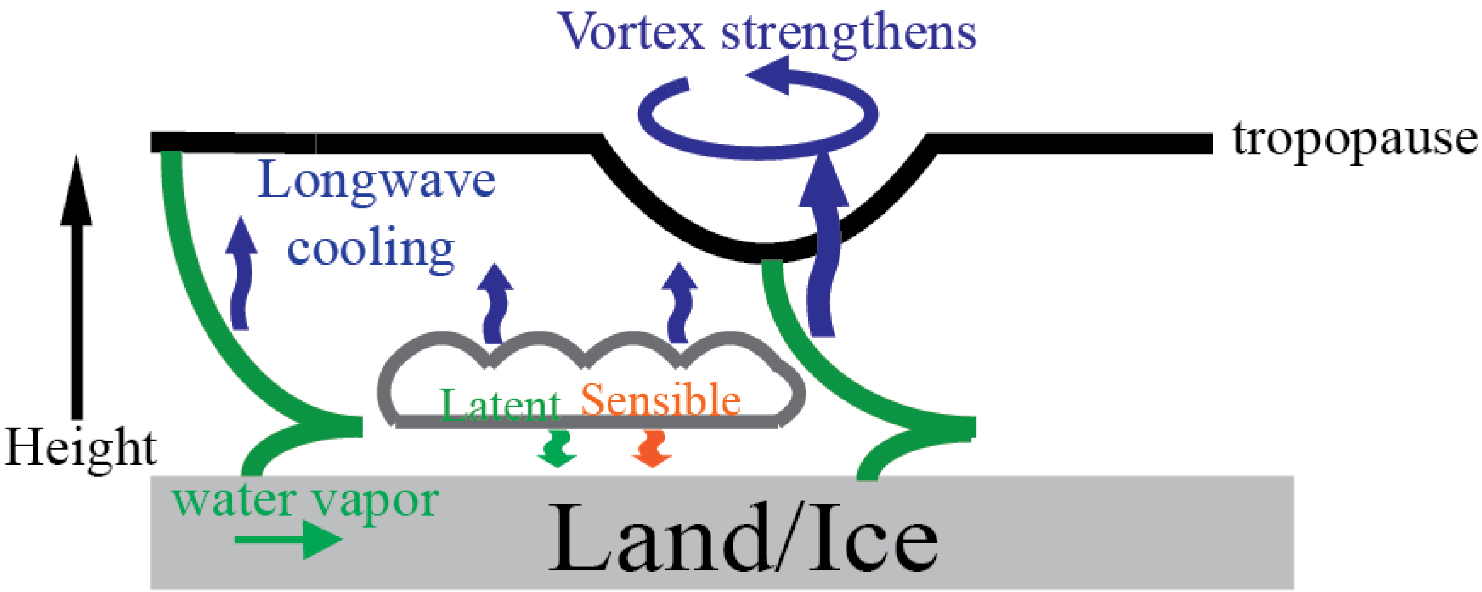


- Restart run on Yellowstone in May 2017
- Bit-equal dependent on compilers, libraries, architecture,...?

TPV dynamics: Ertel's Potential Vorticity

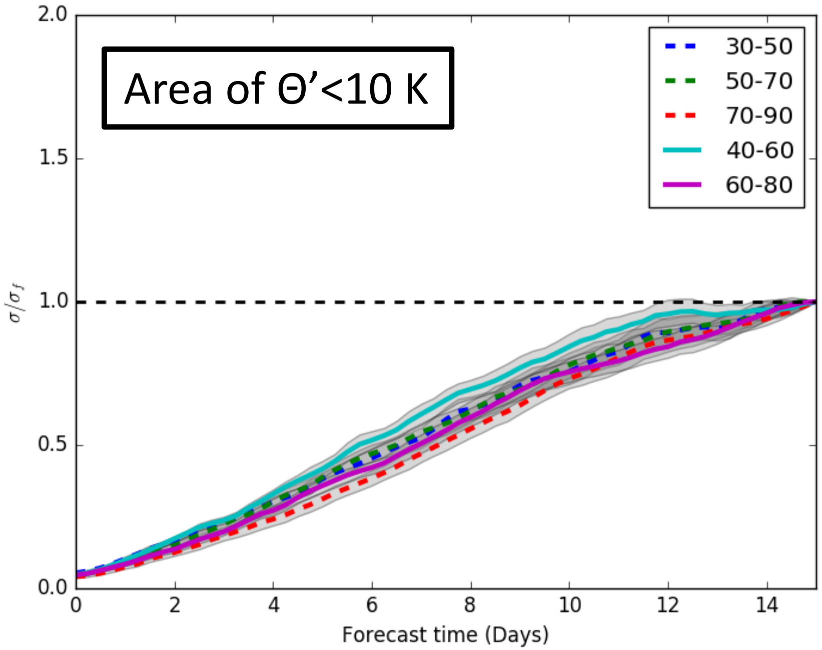
$$\frac{D\Pi}{Dt} = \frac{D}{Dt}\left(\frac{1}{\rho}\boldsymbol{\omega}_a \cdot \nabla\theta\right) = \frac{\boldsymbol{\omega}_a}{\rho} \cdot \nabla \frac{D\theta}{Dt} + \frac{\nabla\theta}{\rho} \cdot \left(\nabla \times \frac{\mathbf{F}}{\rho}\right)$$

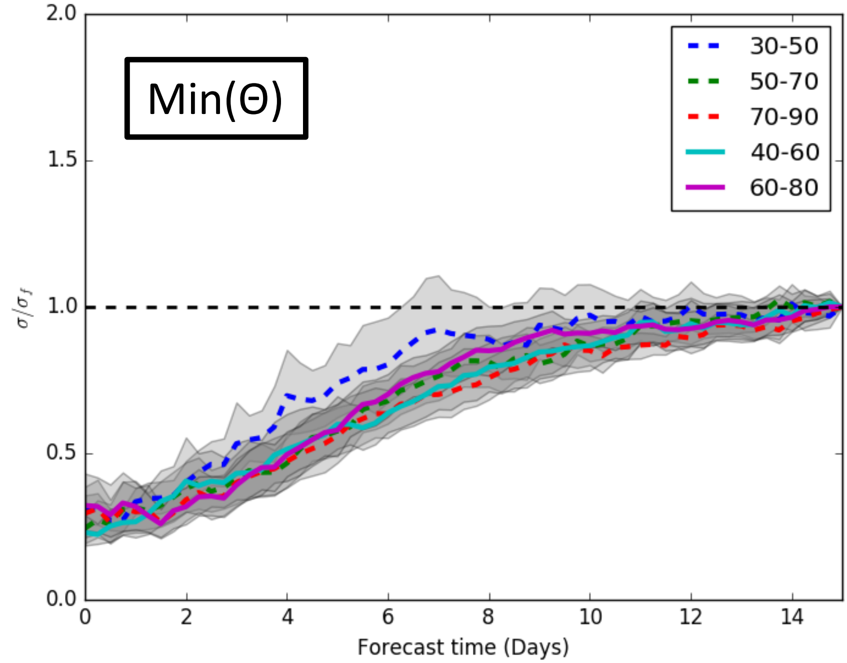
Transport > Diabatic > Frictional

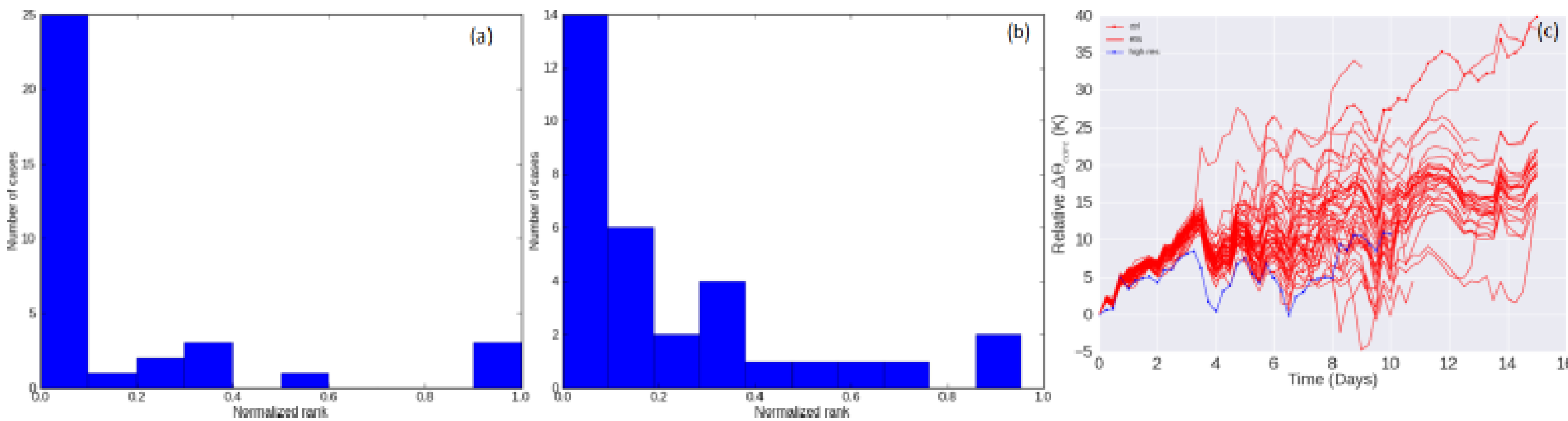


Cavallo & Hakim 2008,2010,2013

Intrinsic and practical TPV predictability in IFS EPS

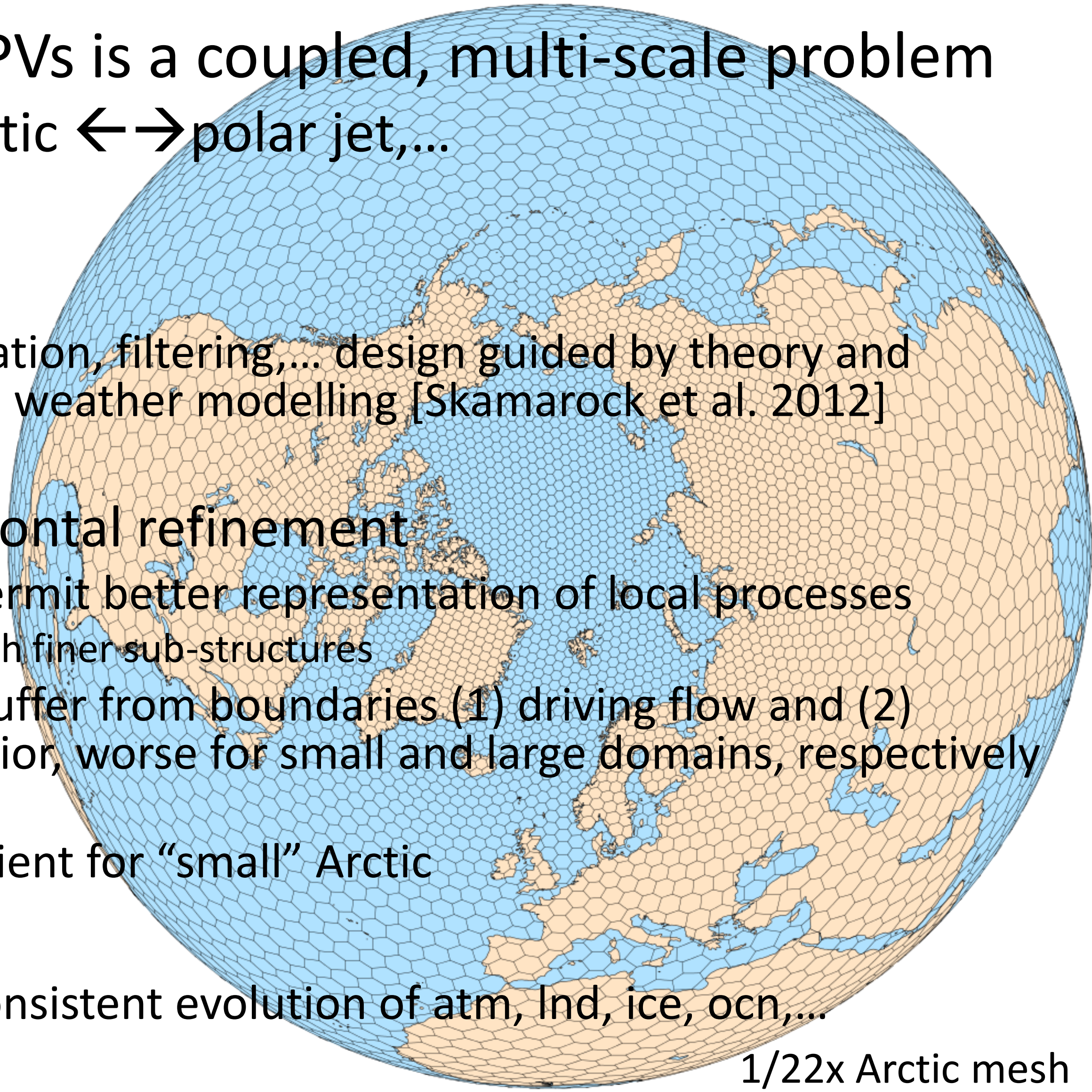






Motivation for MPAS-CESM: Variable-res and coupled permits realism & flexibility

- Representing Arctic/TPVs is a coupled, multi-scale problem
  - e.g., air-ice fluxes, Arctic ←→polar jet,…
- Global MPAS-A
  - Numerics
    - Transport, time integration, filtering,… design guided by theory and practical experience in weather modelling [Skamarock et al. 2012]
    - No polar filter
  - Smooth variable horizontal refinement
    - High-resolution can permit better representation of local processes
      - TPV radii ~500km with finer sub-structures
    - Limited area models suffer from boundaries (1) driving flow and (2) inconsistent with interior, worse for small and large domains, respectively [Laprise et al. 2008]
    - Static refinement efficient for “small” Arctic
- CESM
    - Representation and consistent evolution of atm, lnd, ice, ocn,…



1/22x Arctic mesh