# A climatology of mechanisms that generate intense extratropical cyclones

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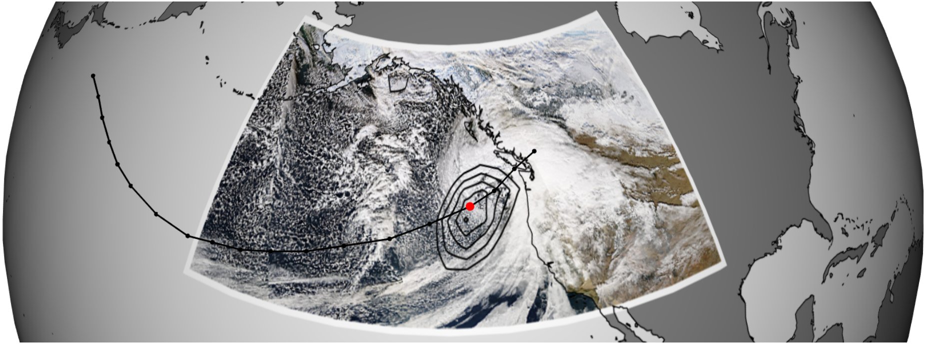
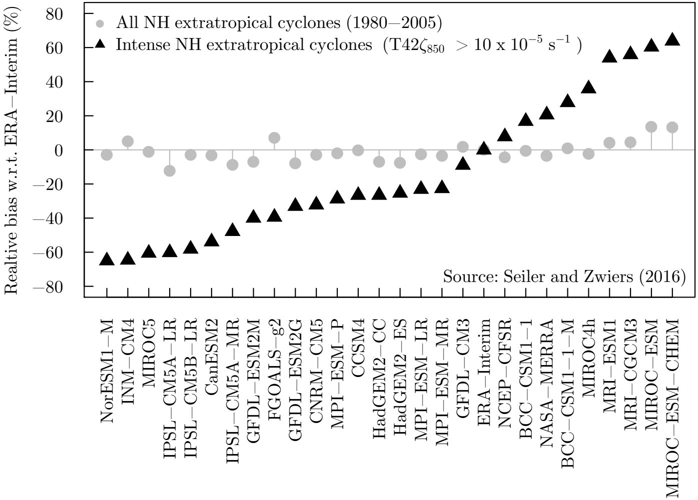


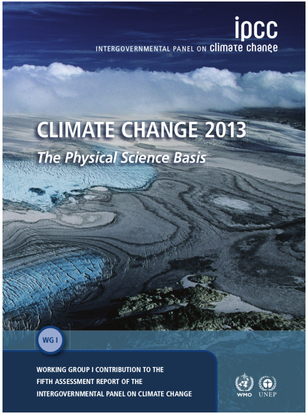
# Global Climate Model (GCM) biases



# IPCC Fifth Assessment Report

**Biases:** "models still [...] underestimate cyclone intensity." (p. 743)

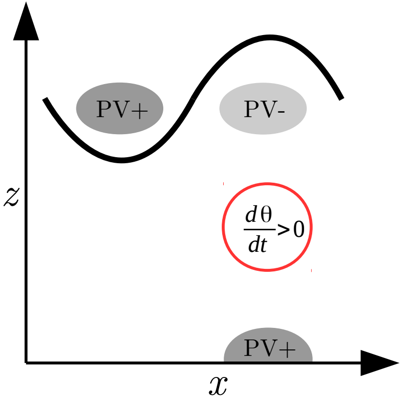
**Projections:** "Substantial uncertainty and thus *low confidence* remains in projecting changes in NH winter storm tracks" (p. 1074)



# Identifying sources of biases and uncertainties in GCMs

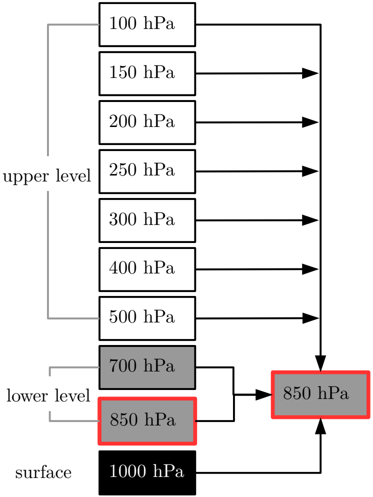
- Statistical approach (e.g. Zappa et al. (2013); Seiler and Zwiers (2016a,b))
- Dynamical approach (e.g. Butler et al., 2010)
- Statistical + dynamical approach (e.g. Woollings et al., 2012)
- We propose: piecewise potential vorticity inversion (Davis and Emanuel, 1991)

# Cyclogenesis from the potential vorticity (PV) perspective



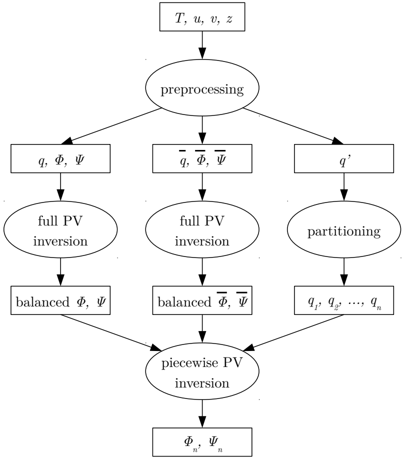

PV = absolute vorticity × static stability (i.e. $q = \frac{1}{\rho}\boldsymbol{\eta} \cdot \nabla\theta$)

# Piecewise potential vorticity inversion



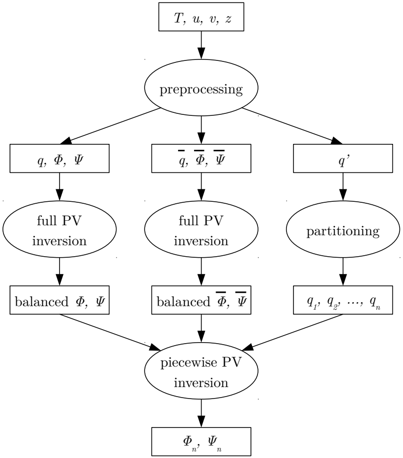
# Full potential vorticity inversion

- Compute $q$ from $T$, $u$, and $v$
- Compute $\Phi$ and $\Psi$ along boundaries of domain
- Decompose $q$, $\Phi$, and $\Psi$ into a 5 day time mean and a perturbation part (e.g. $q = \bar{q} + q'$)
- Specify a balance condition that relates $\Phi$ and $\Psi$ in 2 PDEs:
  - $\Phi = f(\Psi)$
  - $q = f(\Psi, \Phi)$
- *Full* inversion of $q$: solve $\Phi = f(\Psi)$ and $q = f(\Psi, \Phi)$ simultaneously for values of $\Phi$ and $\Psi$ for a given $q$

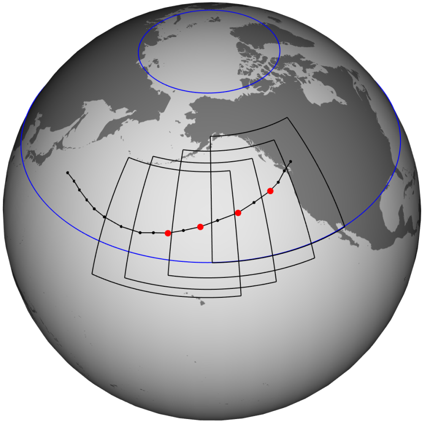


# Piecewise potential vorticity inversion

- Partition $q'$ into $N$ parts $\left(\sum_{n=1}^{N} q_n = q'\right)$
- Invert each individual $q_n$ for $\Phi_n$ and $\Psi_n$
- The sum of all balanced perturbations equals the total balanced perturbation $\left(\sum_{n=1}^{N} \Psi_n = \Psi'\right)$
- Convert stream function to *relative* vorticity $\zeta_n = \nabla^2 \Psi_n$

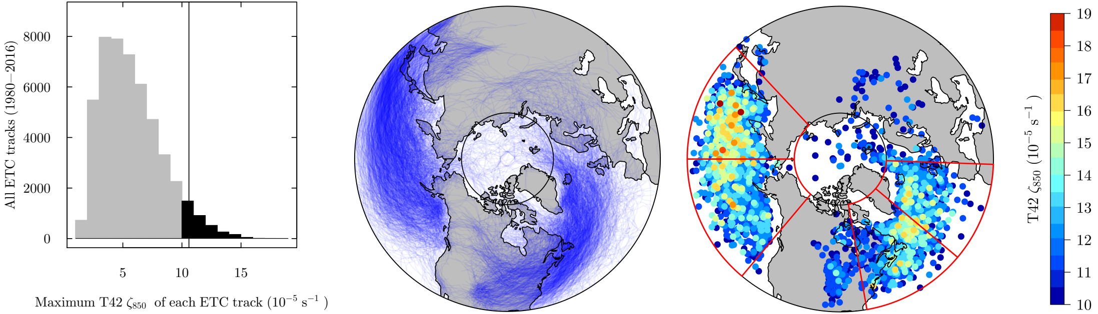


# Data

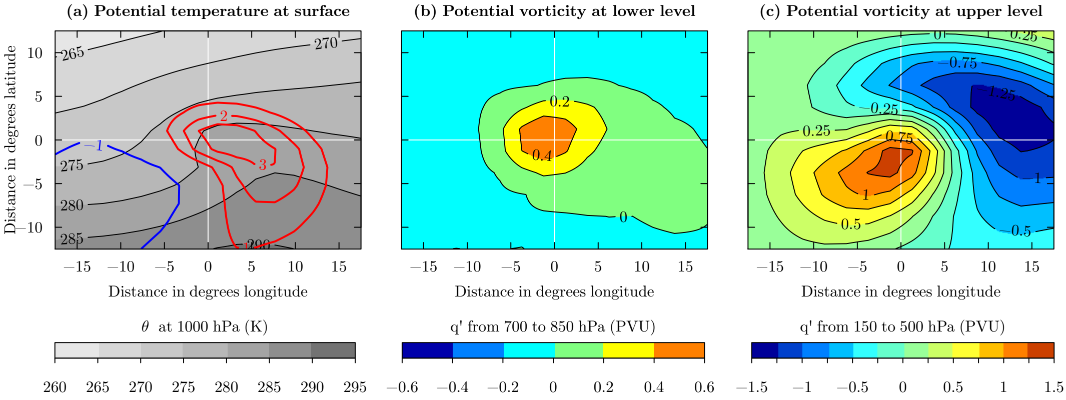


- ERA-Interim reanalysis (1980-2016)
- Cyclone tracking using TRACK (Hodges, 1994)
- PPVI (Davis and Emanuel, 1991): 3273 ETCs, 4 time steps (36h, 24h, 12h, 00h)

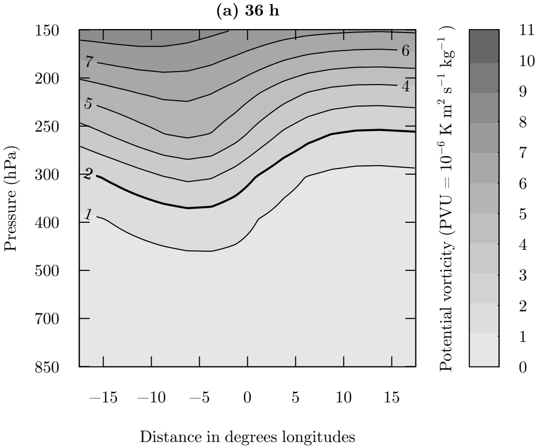
# Identifying intense extratropical cyclones (ETCs)



# Surface temperature, lower-level PV, and upper-level PV



# Potential vorticity (36 h)



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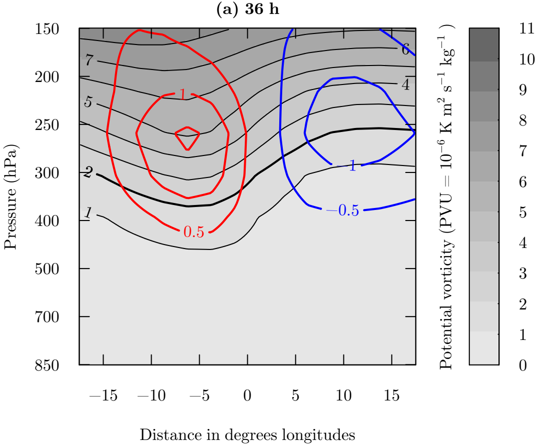
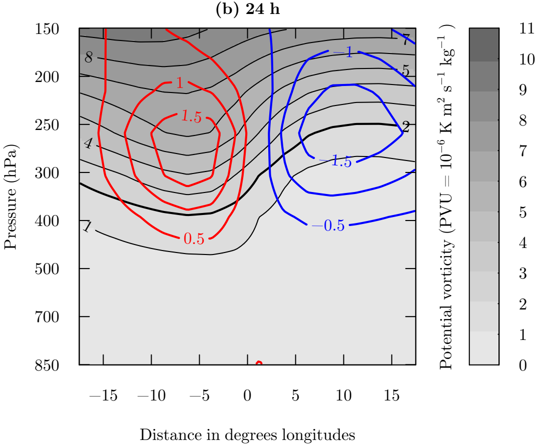
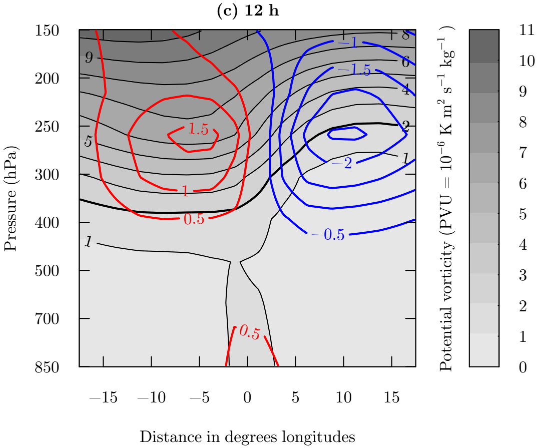


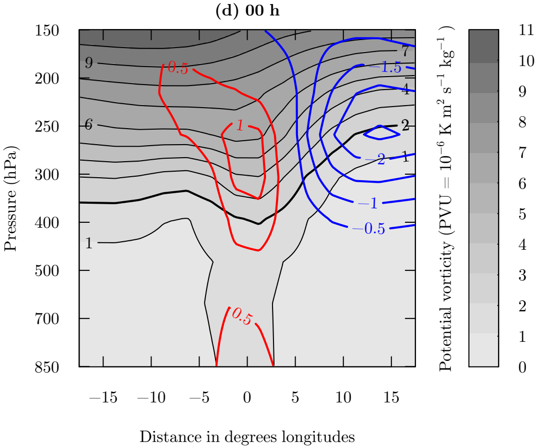
# Potential vorticity (24 h)



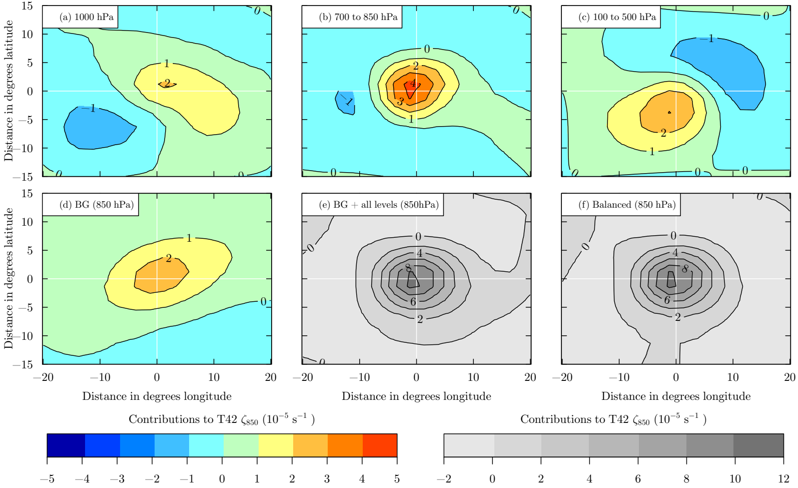
# Potential vorticity (12 h)



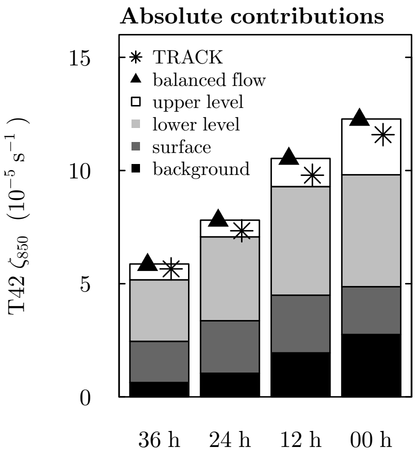
# Potential vorticity (00 h)

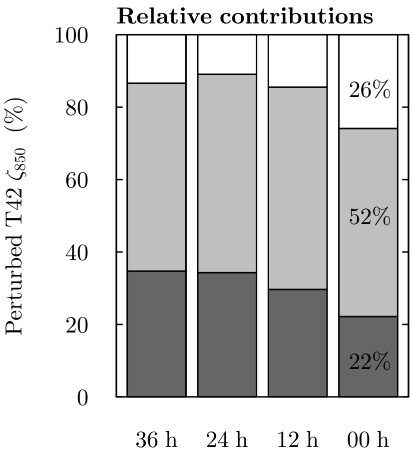


# Does the sum of all contributions match the balanced flow?

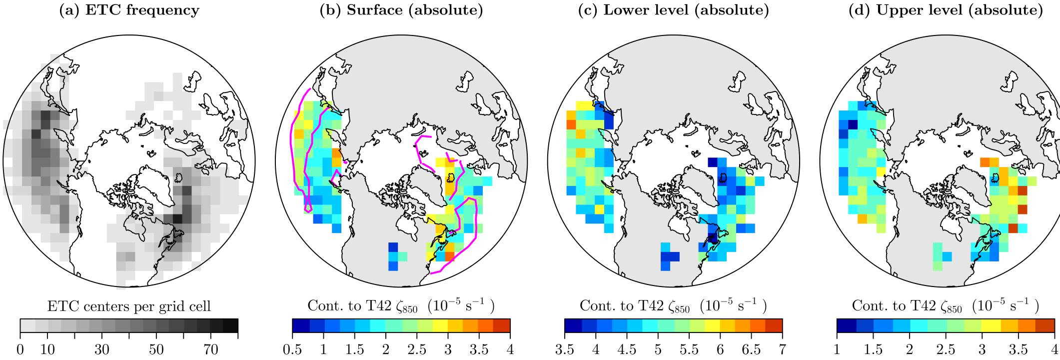


# How do contributions vary during ETC intensification?



# How do contributions vary across ocean basins?



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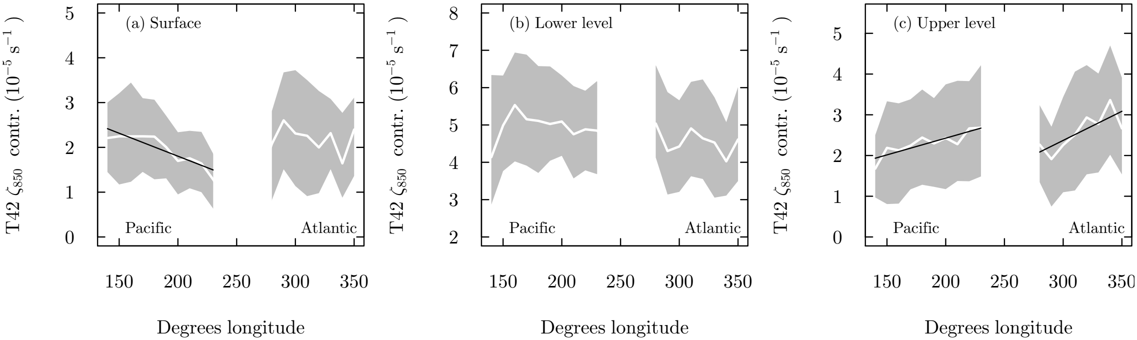
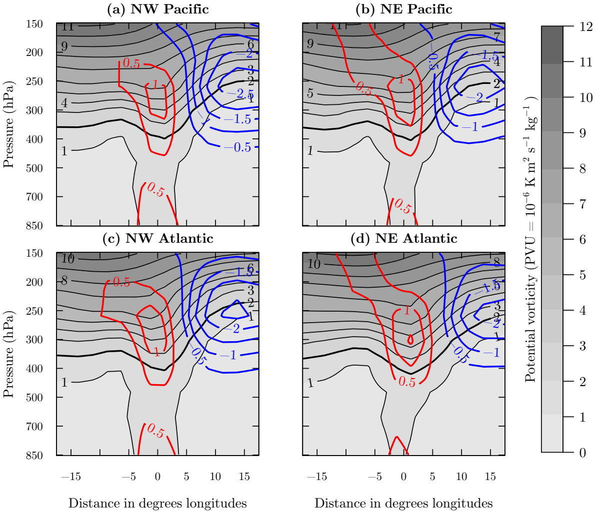


# How do potential vorticity anomalies vary across ocean basins?



# Conclusions

- **Contribution to ETC intensification**
  - Lower level: 52% (latent heating)
  - Upper level: 26% (stratospheric intrusion)
  - Surface: 22% (warm temperature anomalies)
  - Lower-level contributions dominate most cases (74% of ETCs)
- **Regional analysis**
  - Surface contributions *decrease* from West to East (western boundary currents)
  - Upper-level contributions *increase* from West to East (Rossby wave breaking)
- **Research outlook 2018/19**
  - How well do GCMs reproduce these mechanisms?
  - How will mechanisms respond to increasing $CO_2$ concentrations?

# Thank you!

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# Balance and boundary conditions

- Balance condition
  - The horizontal velocity vector $\mathbf{v}$ can be divided into a nondivergent part $\mathbf{v}_\psi$ and an irrotational part $\mathbf{v}_\chi$ (Holton and Hakim, 2013): $\mathbf{v} = \mathbf{v}_\psi + \mathbf{v}_\chi$ , where $\nabla \cdot \mathbf{v}_\psi = 0$ and $\nabla \times \mathbf{v}_\chi = 0$.
  - The balance condition assumes that the magnitude of the irrotational component of the wind is much smaller than the magnitude of the nondivergent wind ($|\mathbf{v}_\chi| \ll |\mathbf{v}_\psi|$), so that terms involving $\mathbf{v}_\chi$ can be neglected.
- Boundary conditions
  - Lateral boundary conditions: $\Phi$ and $\Psi$ (Dirichlet boundary conditions)
  - Vertical boundary conditions: $\frac{\partial \Phi}{\partial z}$ and $\frac{\partial \Psi}{\partial z}$ (Neumann boundary conditions)