Climate Modelling and Sub-seasonal to Seasonal Prediction: Opportunities and Challenges

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Outline

- How good are our climate models?
- Near term climate predictions
- Sources of Uncertainty
  - Convection
  - Resolution
- Sub-seasonal and Seasonal Prediction

How good are our climate models?

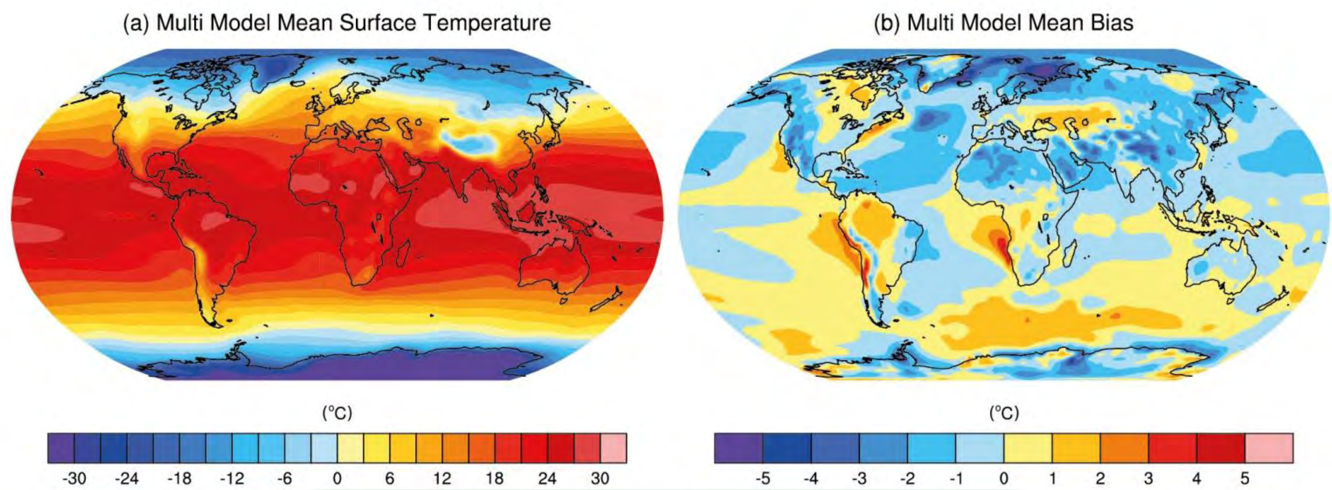
- Some quotes from IPCC AR5, Ch 9: Evaluation of Climate Models *
  - "Climate models have continued to be developed and improved since the AR4,"
  - "The ability of climate models to simulate surface temperature has improved in many, though not all, important aspects relative to the generation of models assessed in the AR4.
    …
    On regional scales (sub-continental and smaller), the confidence in model capability to simulate surface temperature is less than for the larger scales;"
  - The simulation of large-scale patterns of precipitation has improved somewhat since the AR4, although models continue to perform less well for precipitation than for surface temperature.
    …
    At regional scales, precipitation is not simulated as well,"

**Flato, G., J. Marotzke, B. Abiodun, P. Braconnot, S.C. Chou, W. Collins, P. Cox, F. Driouech, S. Emori, V. Eyring, C. Forest, P. Gleckler, E. Guilyardi, C. Jakob, V. Kattsov, C. Reason and M. Rummukainen, 2013: Evaluation of Climate Models. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA*

CMIP5 Multi-model mean Temperatures

- Multi Model Annual mean Temperature biases from the Coupled Model Intercomparison Project Phase 5*
  - Temperature biases are generally less than 2°C except for a few areas including
    - Coastal Upwelling areas, high elevations and near the ice edge
  - Magnitude of the seasonal cycle is generally overestimated over extra-tropical land, and under-estimated over the extra-tropical oceans

*

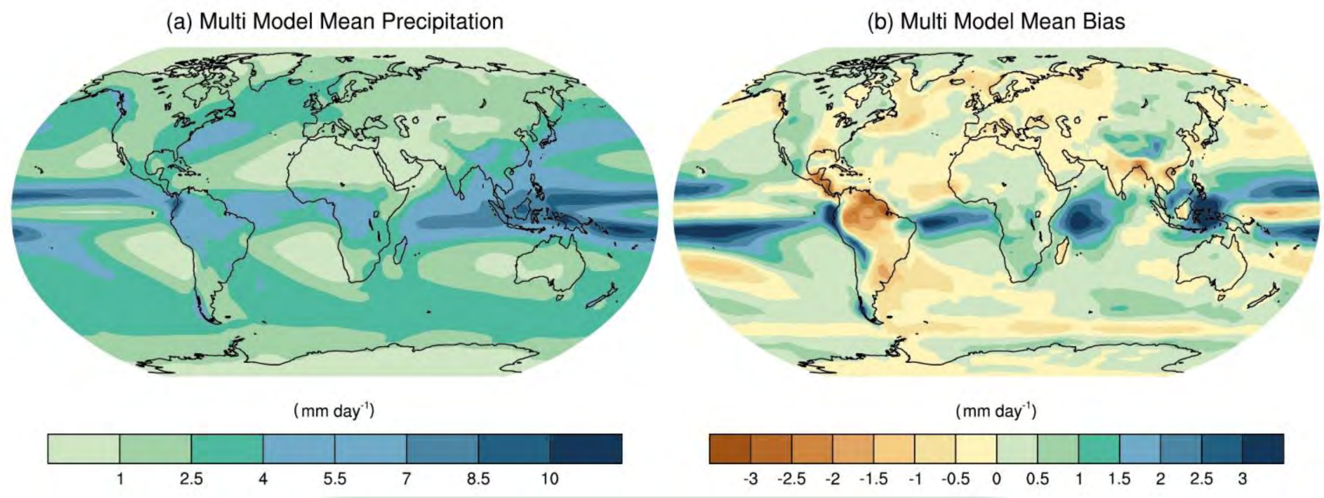


from Fig 9.2 of the IPPC AR5 WG1 Report

CMIP5 Multi-model mean Precipitation

- Multi Model Annual mean Precipitation biases from the Coupled Model Intercomparison Project Phase 5*
  - Large Scale Pattern Moderately well capture but large tropical biases
    - Excessive precipitation in western equatorial Indian Ocean, Tropical Convergence Zones
    - Deficient precipitation over equatorial South America, Indian Sub-continent, equatorial west Pacific
  - Some of these biases represent relative errors in excess of 50% and can be larger than 75%

*



from Fig 9.4 of the IPPC AR5 WG1 Report

CMIP5 Projections of Near term Climate Change

- Drawn from IPCC AR5, Ch 11: Near-term Climate Change: Projections and Predictability *
  - Projections rather than predictions, that is they have not been initialized with the current state of the climate system but are extensions of simulations of the recent historical period
  - Based on a medium emissions scenario
  - Relative to 1986-2005

On the following few figures

- **Stippling** indicates that the multi-model mean change is more than two standard deviations of the interannual variability of the last 20 years **and** more than 90% of the models agree on the sign of the change

Signal is large and the models agree

- **Hatching** indicates that the change is less than one standard deviation of the interannual variability of the last 20 years

Signal is small or the models disagree

** Kirtman, B., S.B. Power, J.A. Adedoyin, G.J. Boer, R. Bojariu, I. Camilloni, F.J. Doblas-Reyes, A.M. Fiore, M. Kimoto, G.A. Meehl, M. Prather, A. Sarr, C. Schär, R. Sutton, G.J. van Oldenborgh, G. Vecchi and H.J. Wang, 2013: Near-term Climate Change: Projections and Predictability. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.*

Change in Surface Air Temperature, 2016-2035

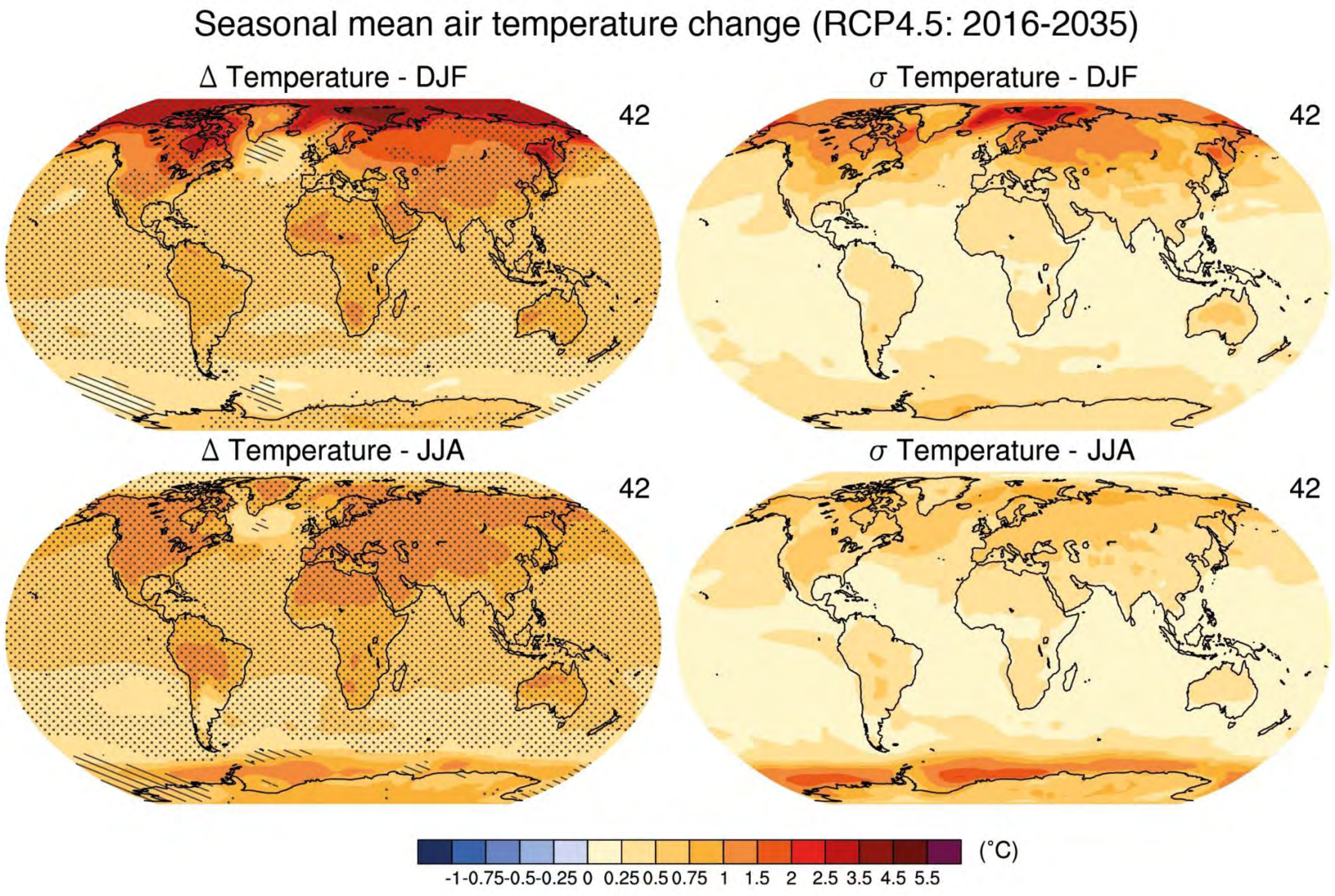


Fig 11.10 of the IPPC AR5 WG1 Report

Change in Precipitation, 2016-2035

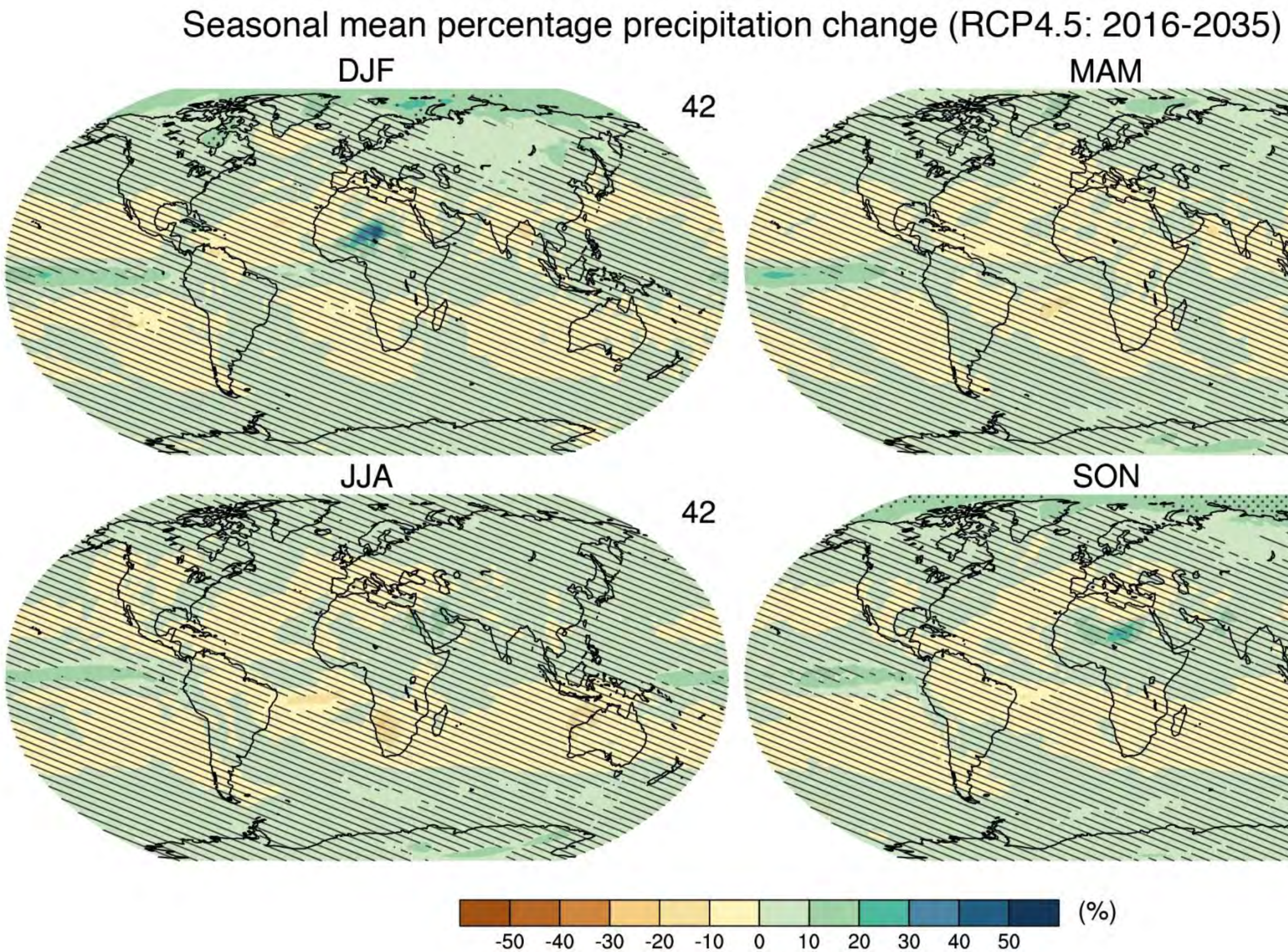
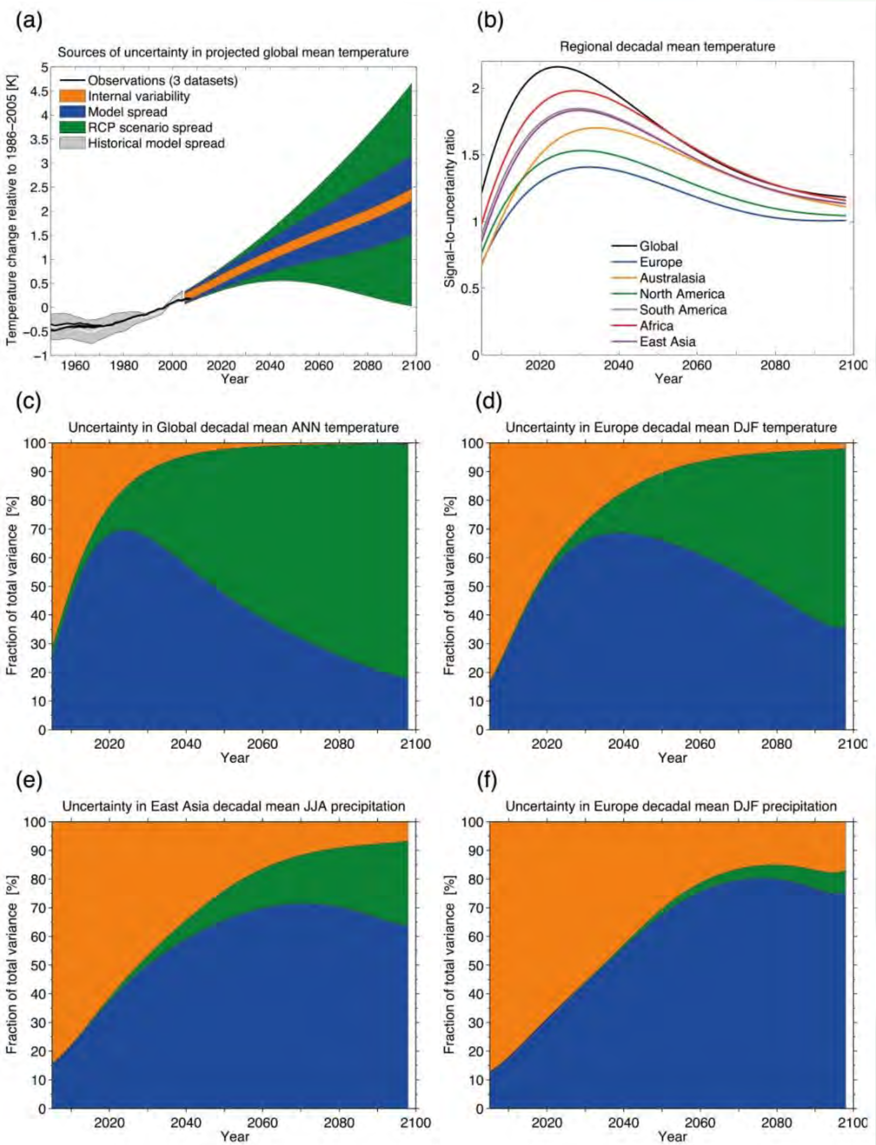


Fig 11.12 of the IPPC AR5 WG1 Report

Sources of Uncertainty

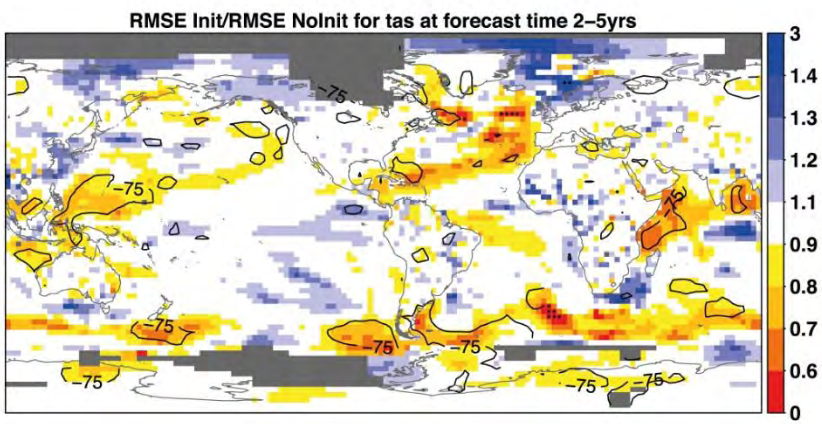


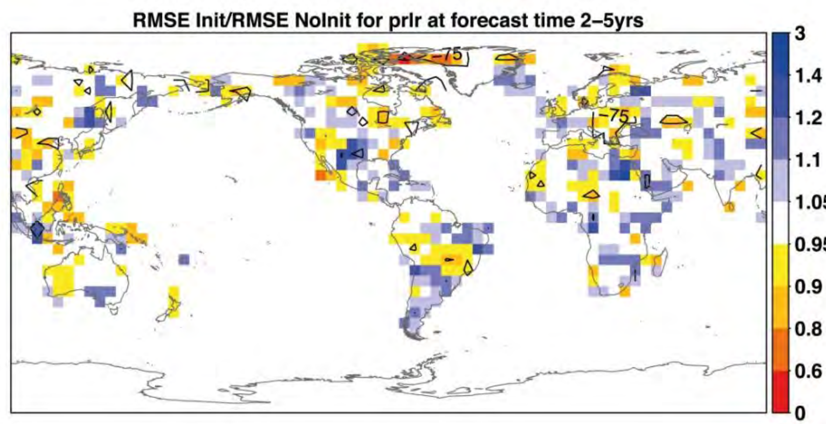
- Hawkins and Sutton (2009,2011) developed a method for partitioning the spread (uncertainty) in climate projections between
- **Internal variability;** accounting for natural variability in the climate system
- **Model response uncertainty;** accounting for the fact that different models have a different response to a given forcing
- **Scenario Uncertainty;** accounting for the fact that we don't know how future emissions will change
- For near term major sources of uncertainty are associated with **internal variability** and **model uncertainty**

Fig 11.14 of the IPPC AR5 WG1 Report following Hawkins and Sutton (2009,2011)

Internal Variability

- In decadal means, these depends on long timescale models of variability in the climate system
  - For the global mean this decadal variability is large related to changes in the ocean circulation which affect the rate at which heat is taken up by the ocean
  - This uncertainty can potentially be narrowed through the use of simulations in which the ocean circulation in particular is initialized close to observations
- CMIP5 included for the first time an set of initialized decadal "hindcasts" of the late 20th century to test the skill of decadal prediction systems





From Figs 11.4 and 11.6 of the IPPC AR5 WG1 Report Following Doblas Reyas et al. (2013)

Model Uncertainty

- Climate models are not perfect
  - We have a set of mathematical equations which describe the evolution of the atmosphere but we cannot solve them exactly
  - Climate models solve these equations numerically, however we cannot simulate all the scales of motion in the atmosphere
  - For the resolved scales of motion (50-250km and larger) our numerical techniques are pretty good.
  - For scales smaller than the resolution of the climate model we have to use ***physically based parametrizartion schemes*** to represent the effects of the unresolved processes e.g.
    - Cloud microphysics
    - Turbulent transport in the atmospheric boundary layer
    - Convection
    - Interactions with energy and momentum transfer between the surface and the atmosphere
    - Interaction with orography
    - Radiation
  - Uncertainties (errors) in these parametrization schemes are the largest source of model uncertainty

Sensitivity to the representation of convection

Some examples from within in the NCAS Climate tropical group

(Nicholas Klingaman, Stephanie Bush, Linda Hirons, Chris Holloway)

- Changing one parameter in the convection scheme (entrainment rate) which controls mixing between clouds and the environment
  - Impact on the bias
  - Impact on variability

Holloway, C. E., Woolnough, S. J. and Lister, G. M. S. (2015) The effects of explicit versus parameterized convection on the MJO in a large-domain high-resolution tropical case study. Part II: Processes leading to differences in MJO development, *Journal of the Atmospheric Sciences*, in press

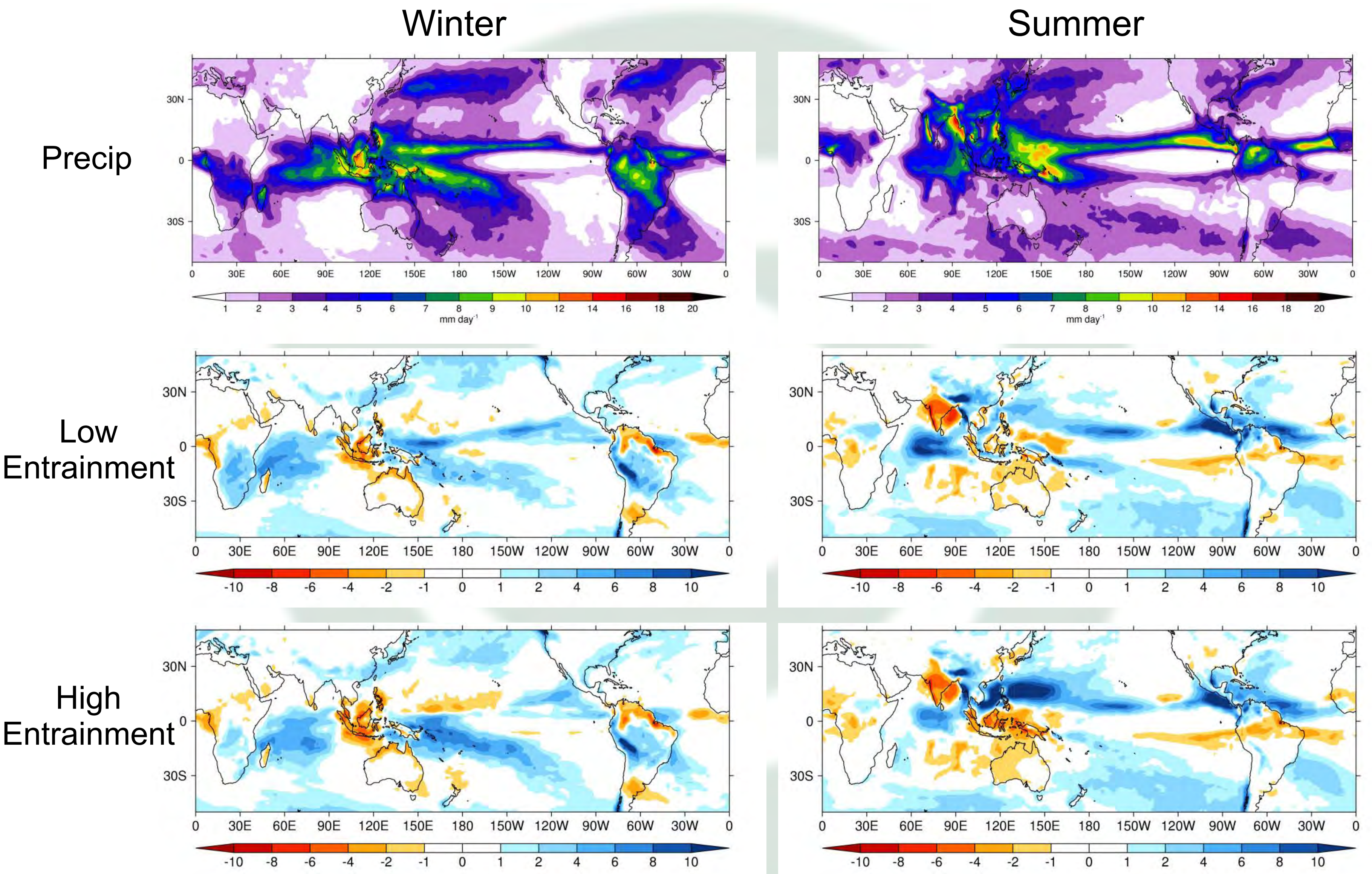
Bush, S. J., Turner, A. G., Woolnough, S. J., Martin, G. M. and Klingaman, N. P. (2015) The effect of increased convective entrainment on Asian monsoon biases in the MetUM General Circulation Model. *Quarterly Journal of the Royal Meteorological Society*. **140**, 311-326

Klingaman, N. and Woolnough, S. (2014) The role of air–sea coupling in the simulation of the Madden–Julian oscillation in the Hadley Centre model. *Quarterly Journal of the Royal Meteorological Society,* **140**, 2272-2286.

Klingaman, N. and Woolnough, S. (2014) Using a case-study approach to improve the Madden-Julian oscillation in the Hadley Centre model. *Quarterly Journal of the Royal Meteorological Society*, **140,** 2491-2505.

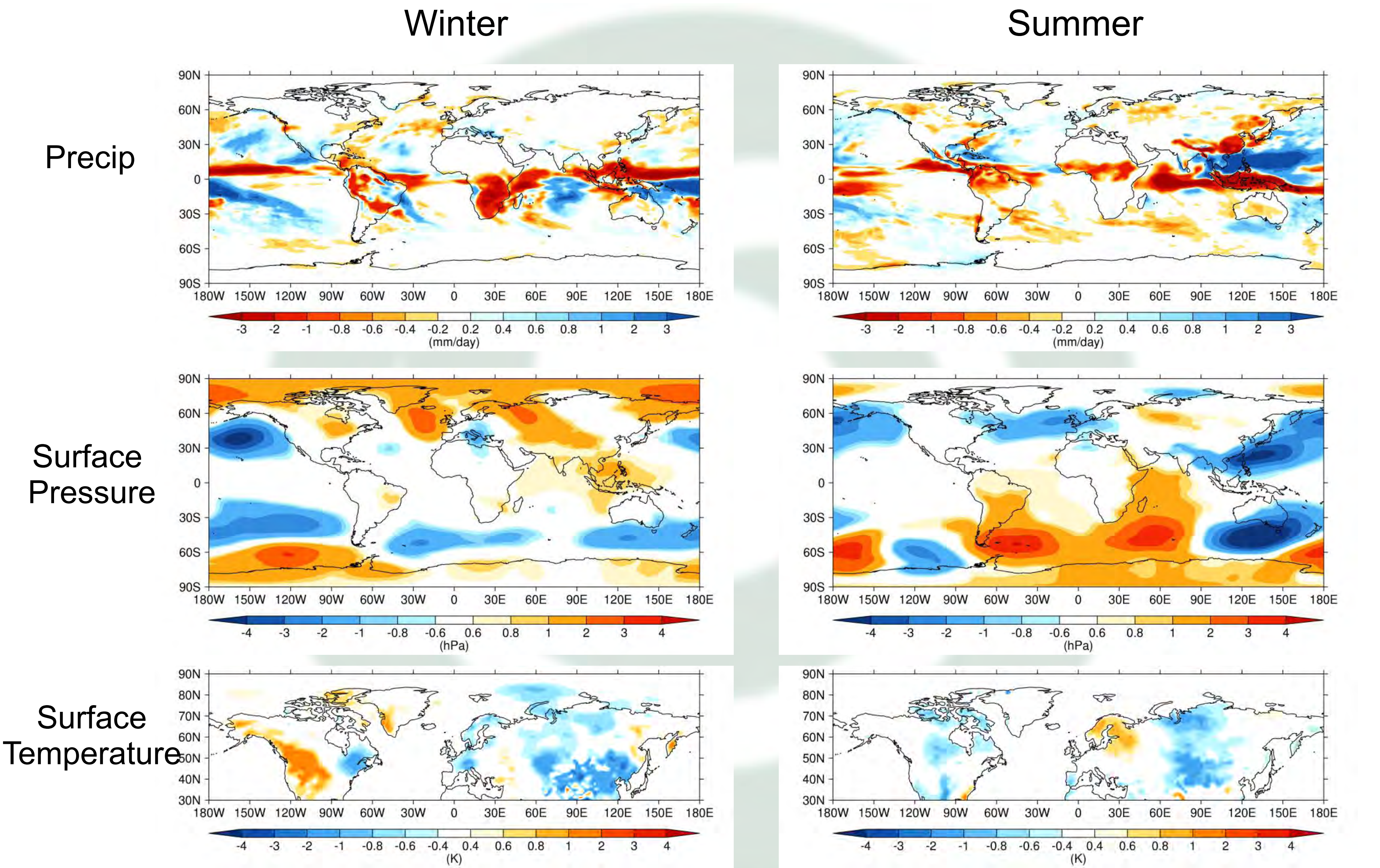
Holloway, C. E., Woolnough, S. J. and Lister, G. M. S. (2013) The effects of explicit versus parameterized convection on the MJO in a large-domain high-resolution tropical case study. Part I: Characterization of large-scale organization and propagation. *Journal of the Atmospheric Sciences*, **70**,1342-1369.

Sensitivity to the representation of convection



Figures courtesy of Linda Hirons

Sensitivity to the representation of convection



Figures courtesy of Linda Hirons

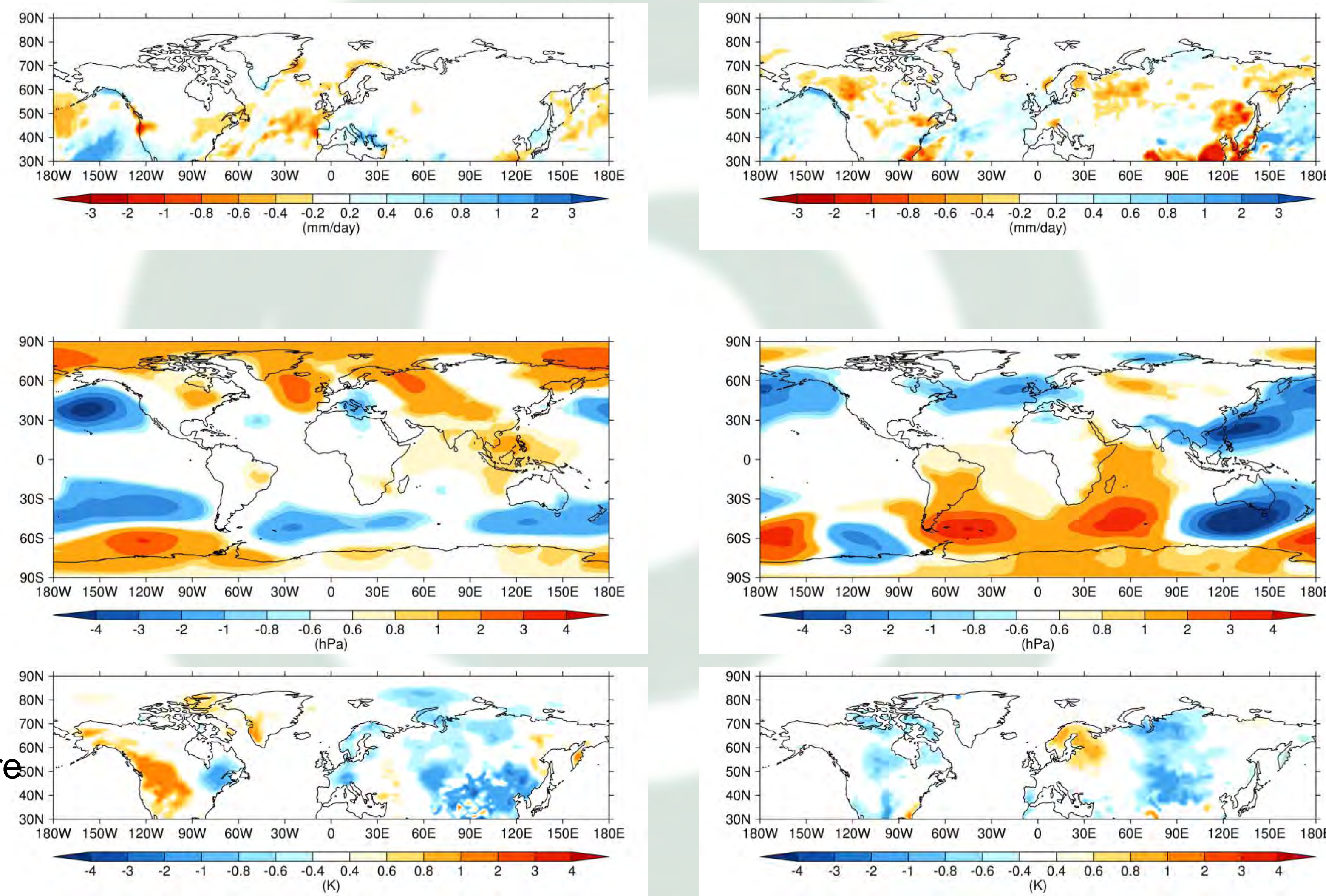
Sensitivity to the representation of convection

Winter | Summer

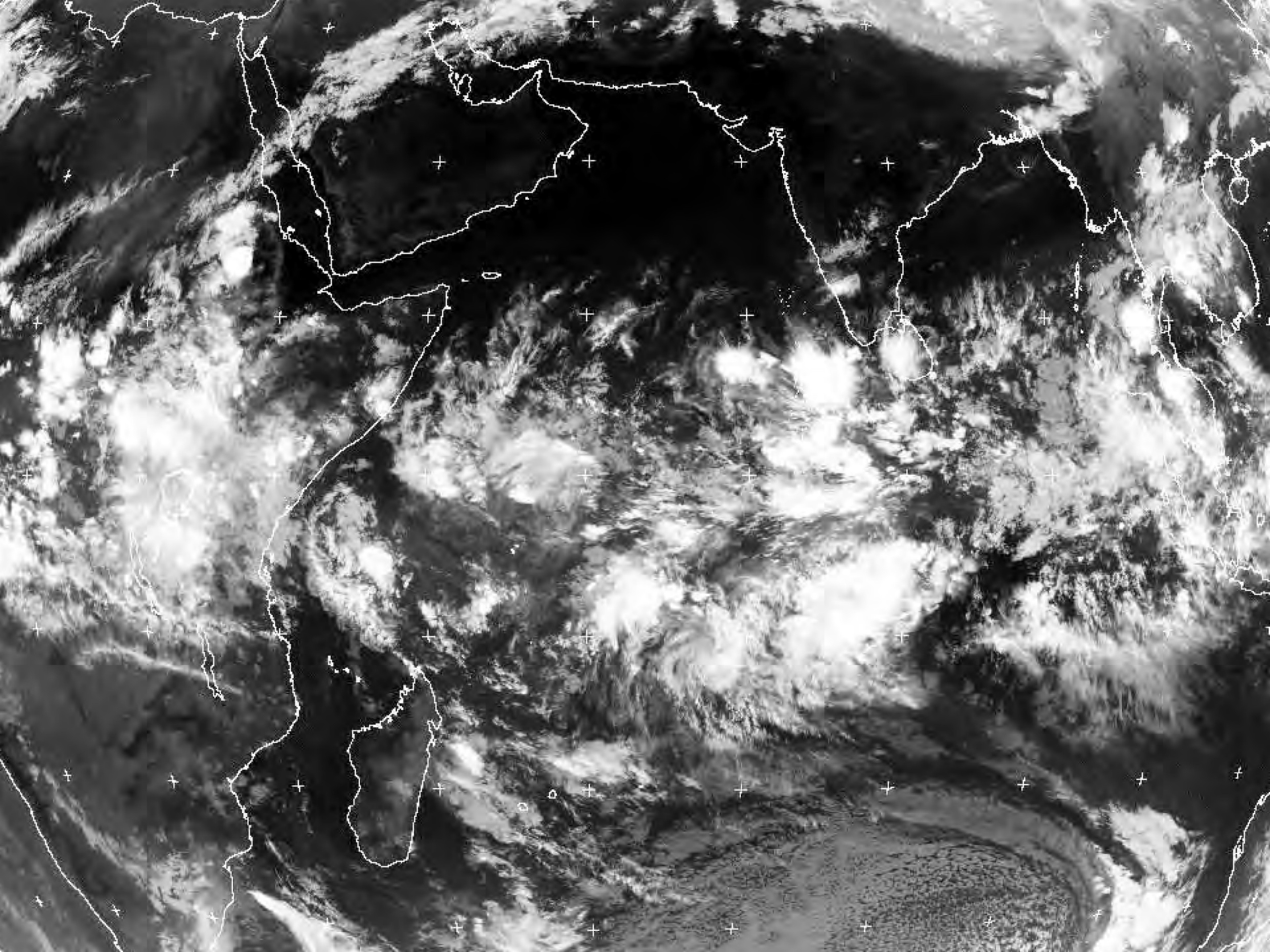
Precip

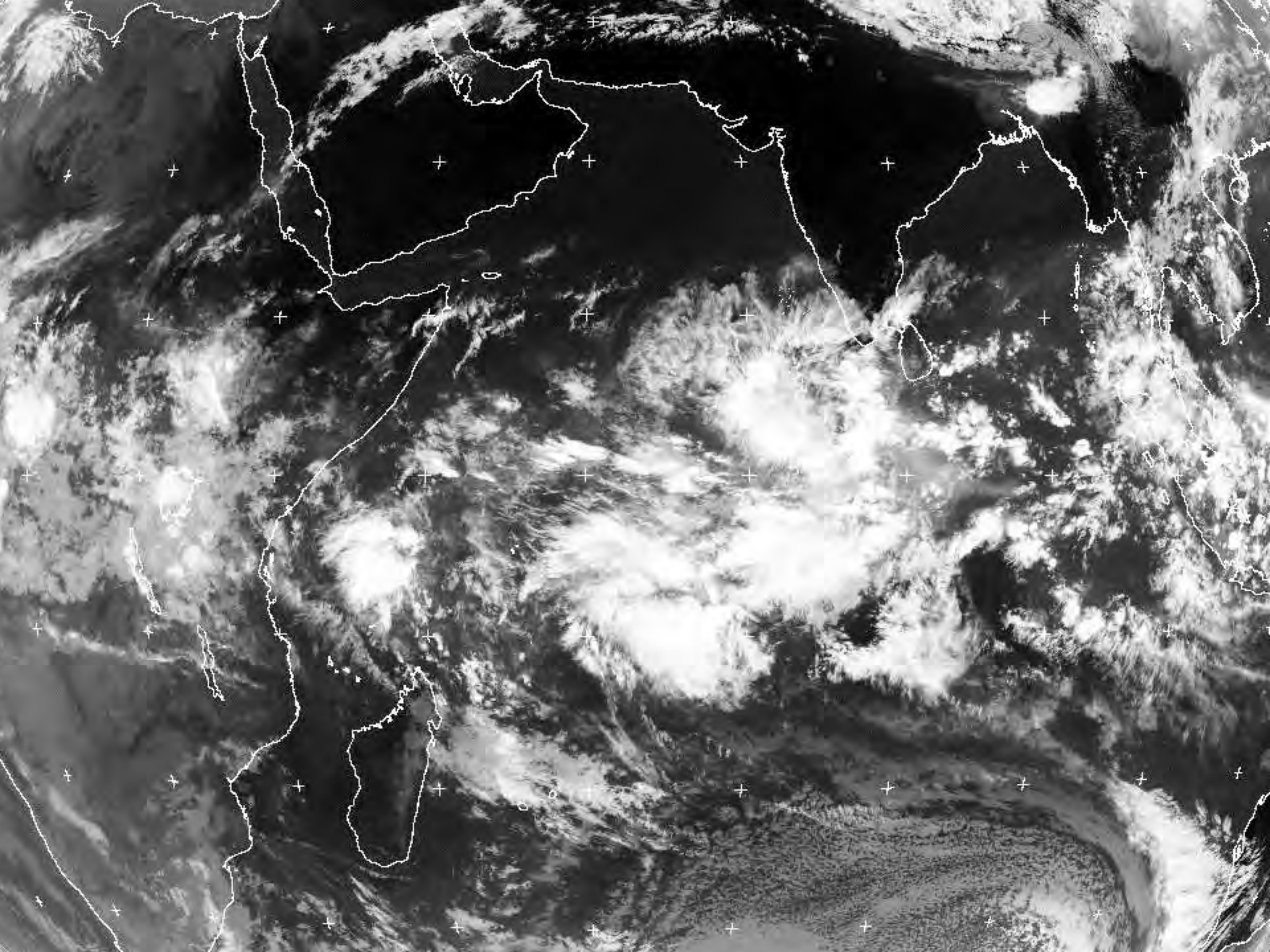
Surface Pressure

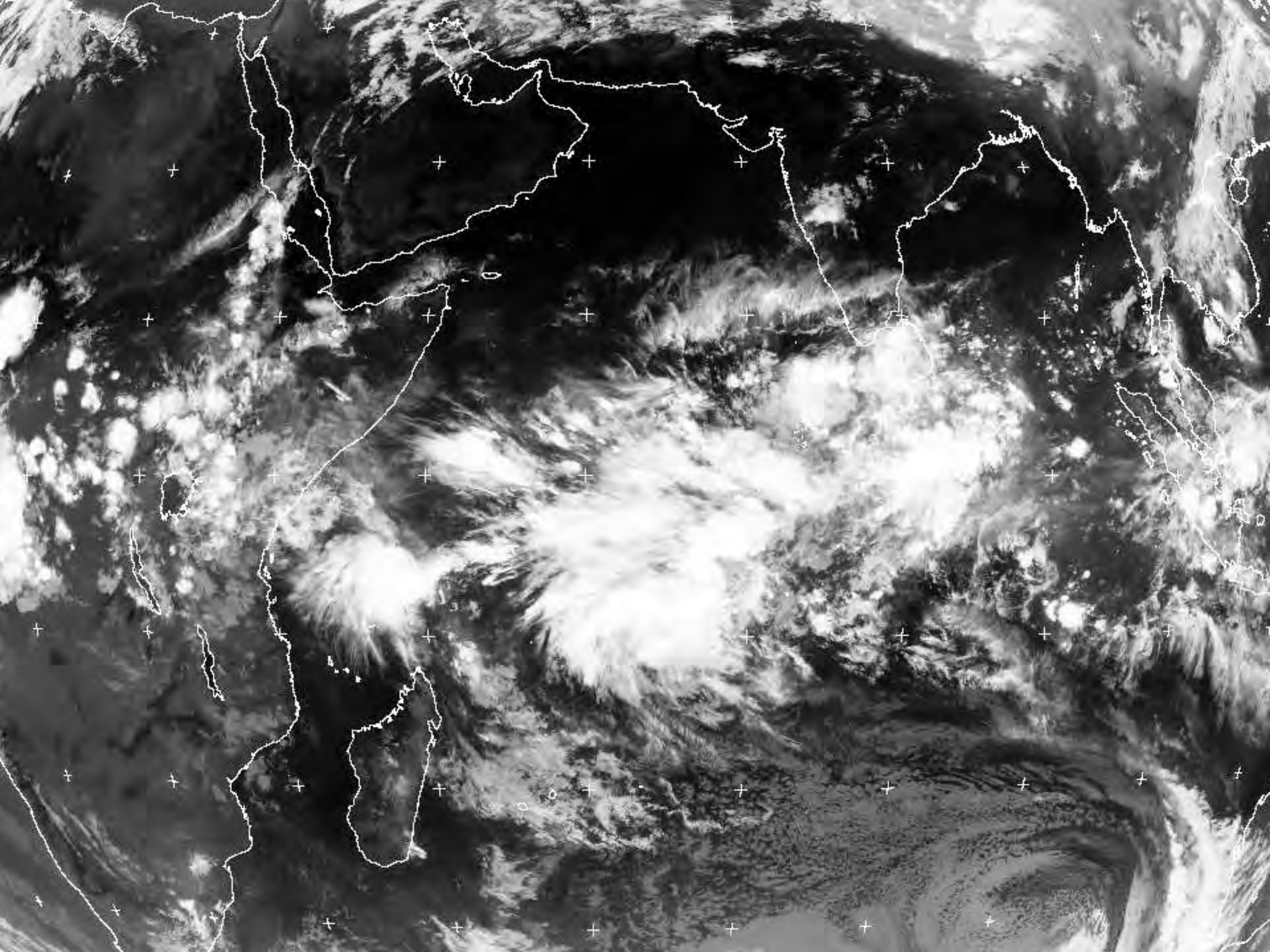
Surface Temperature

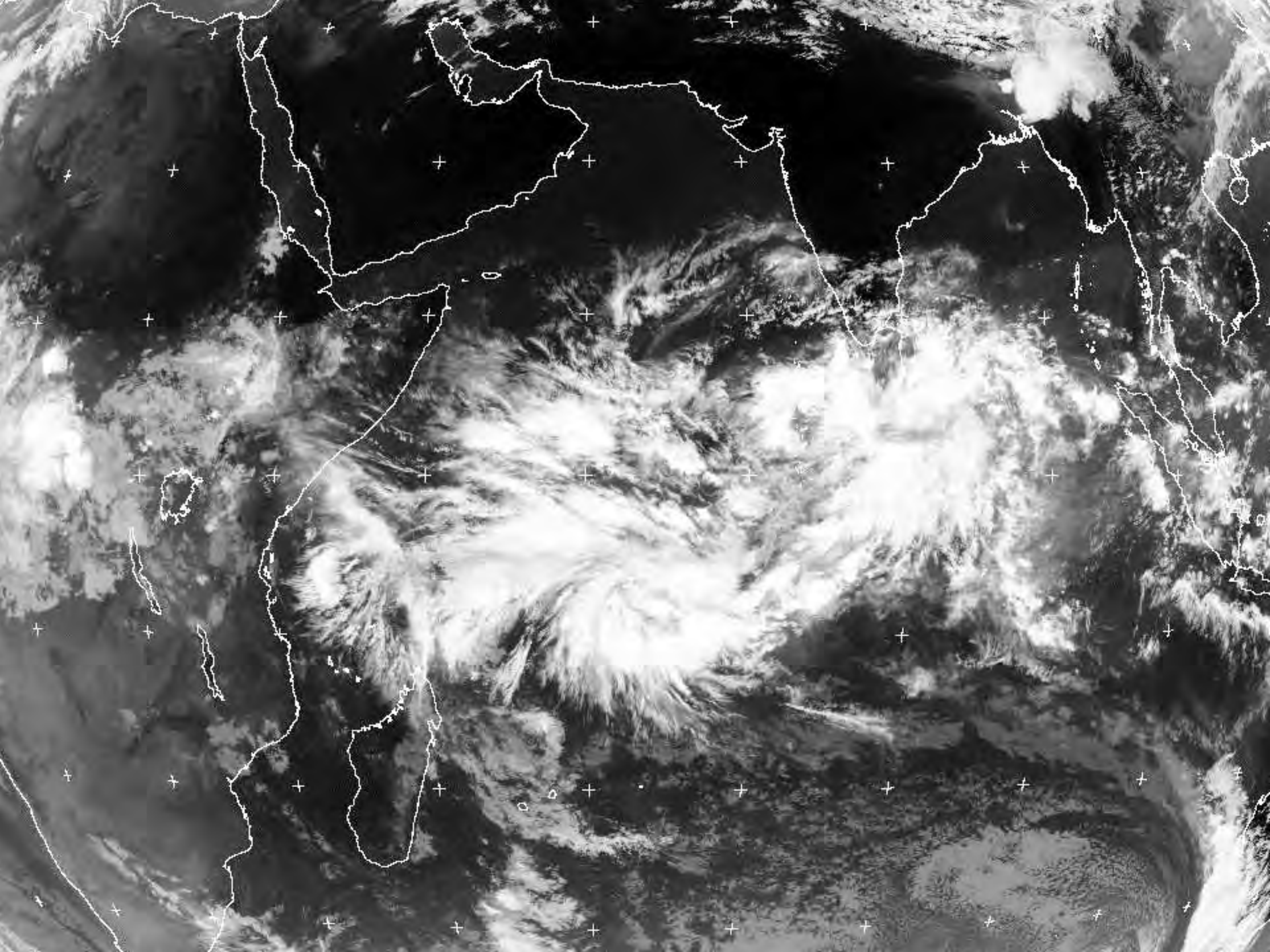


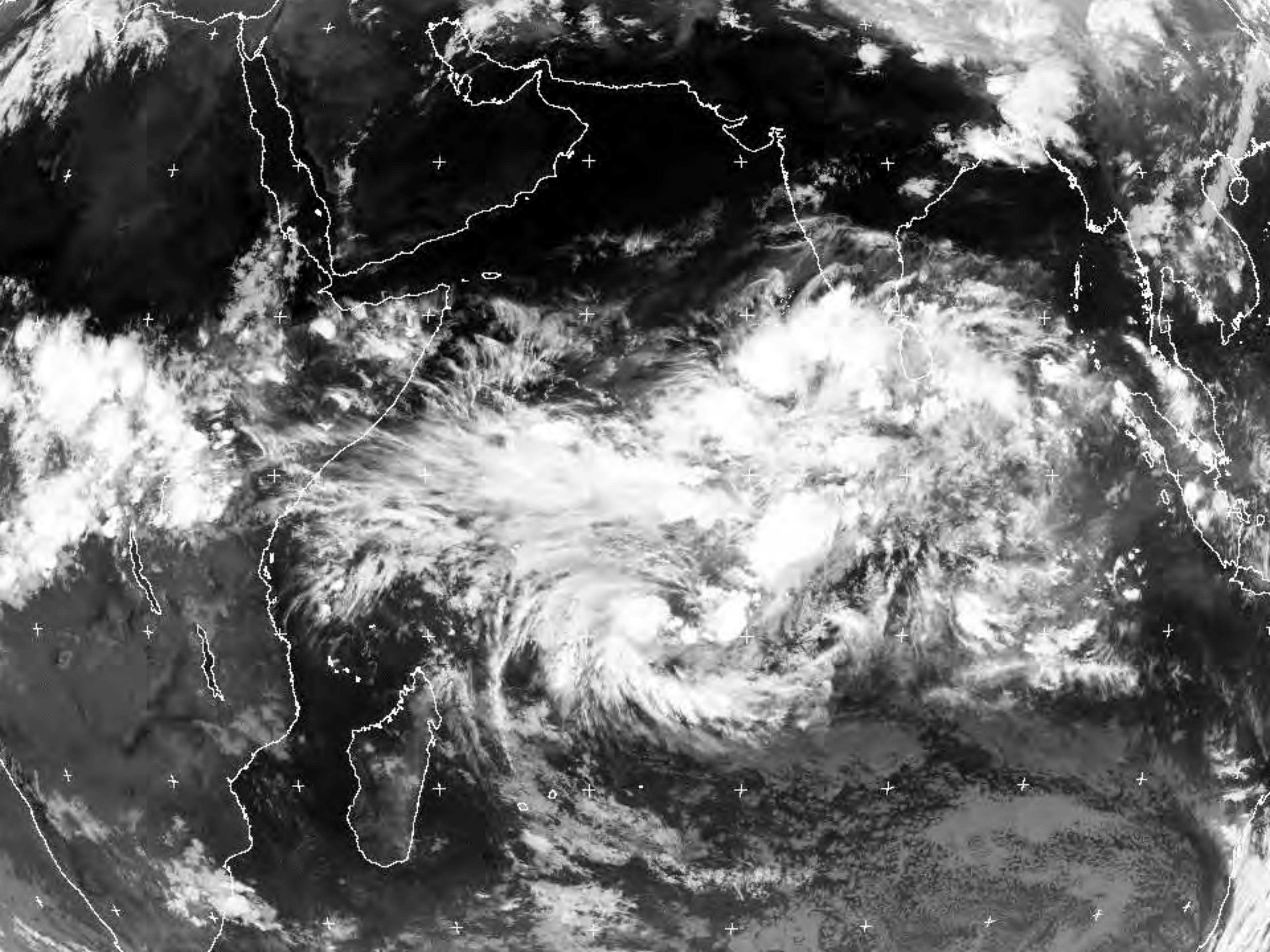
Figures courtesy of Linda Hirons

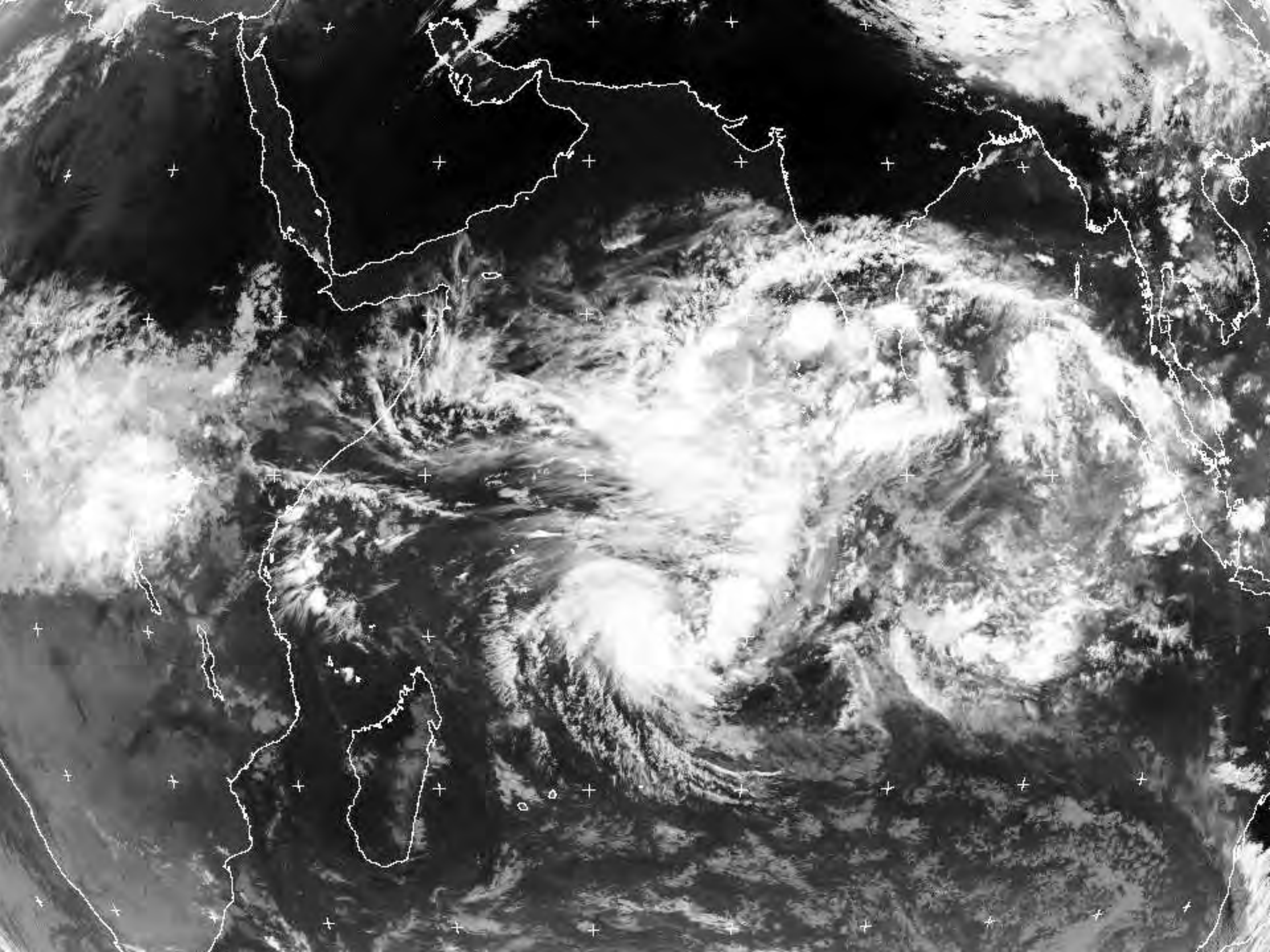


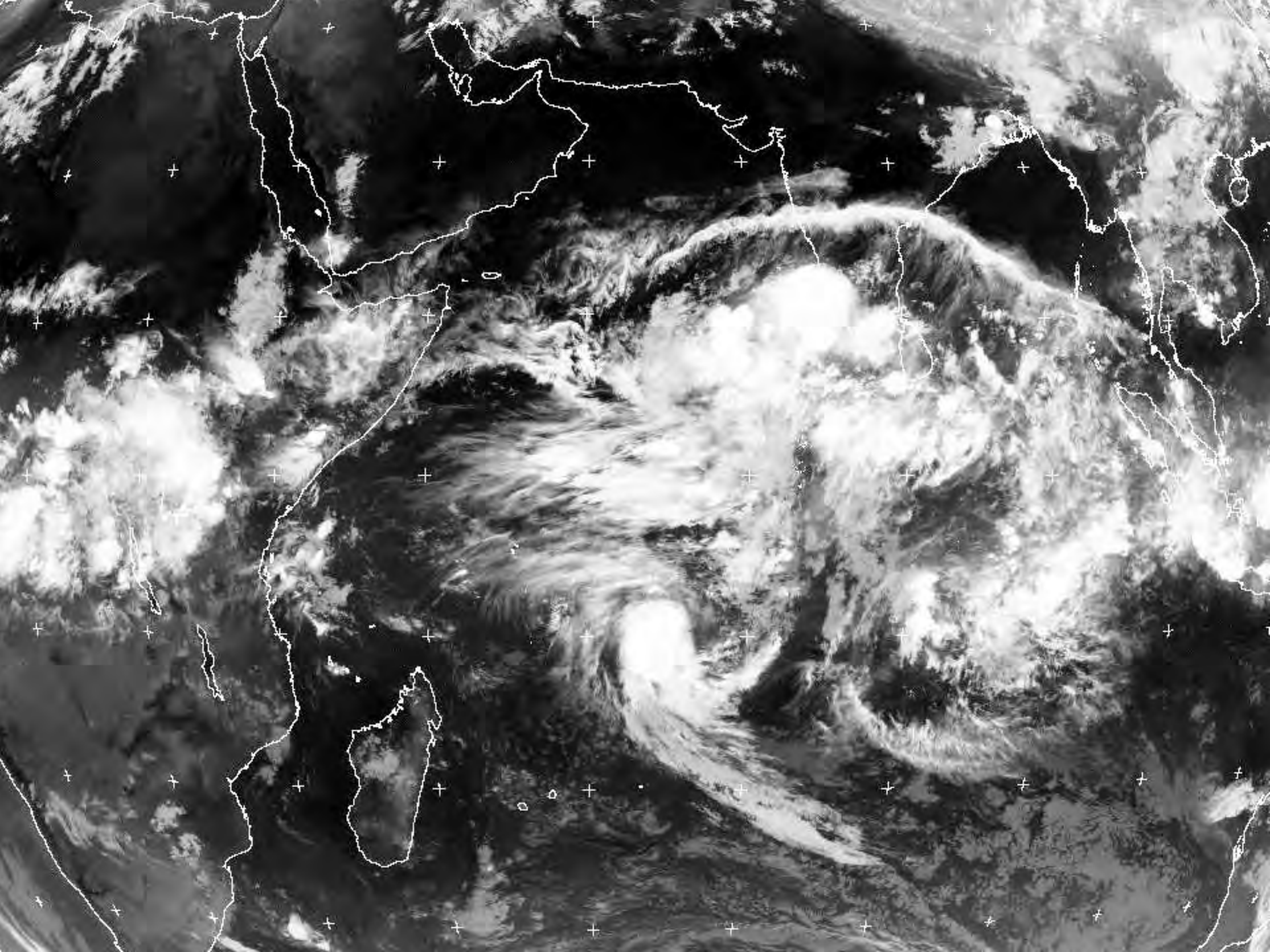


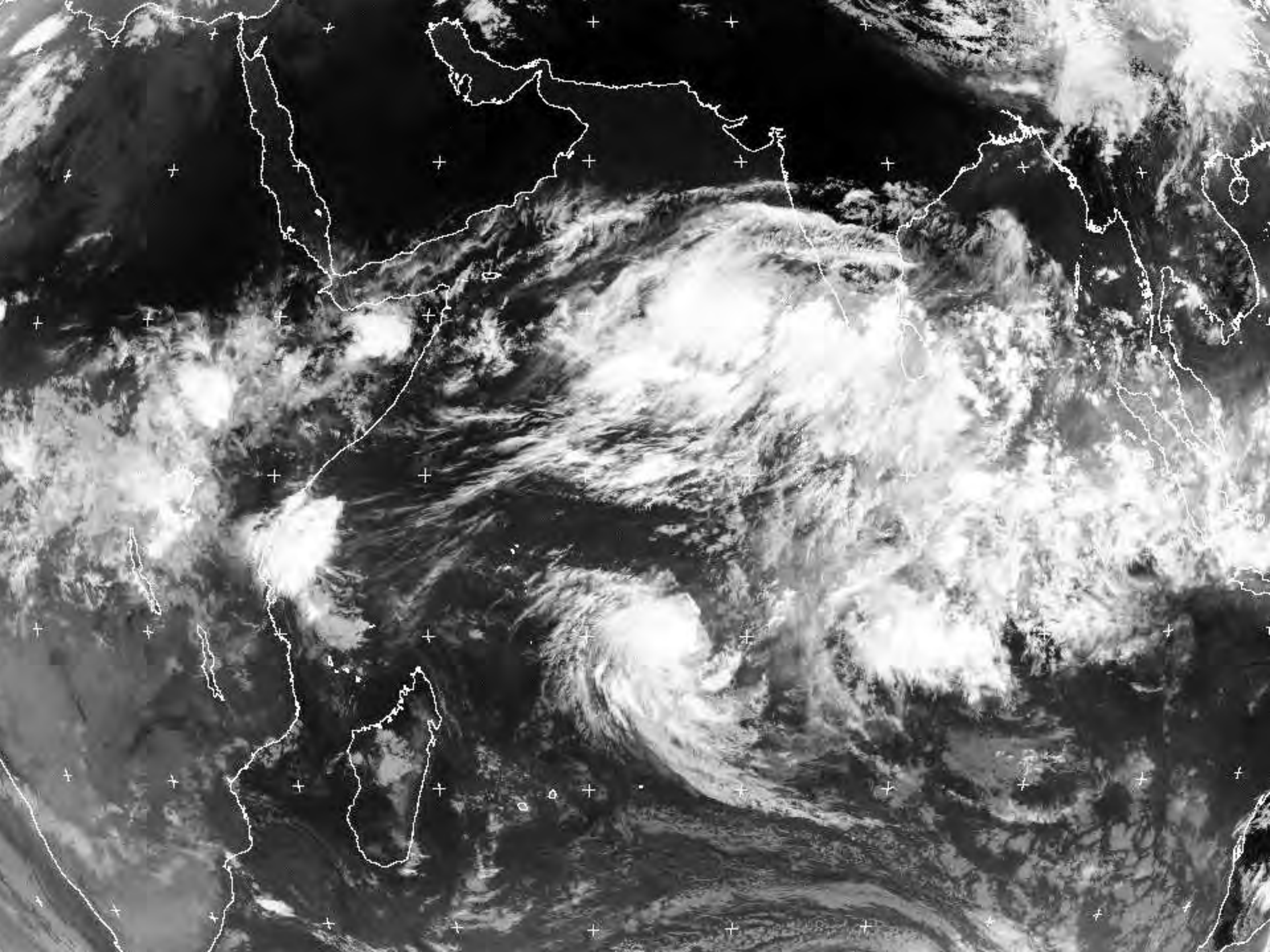


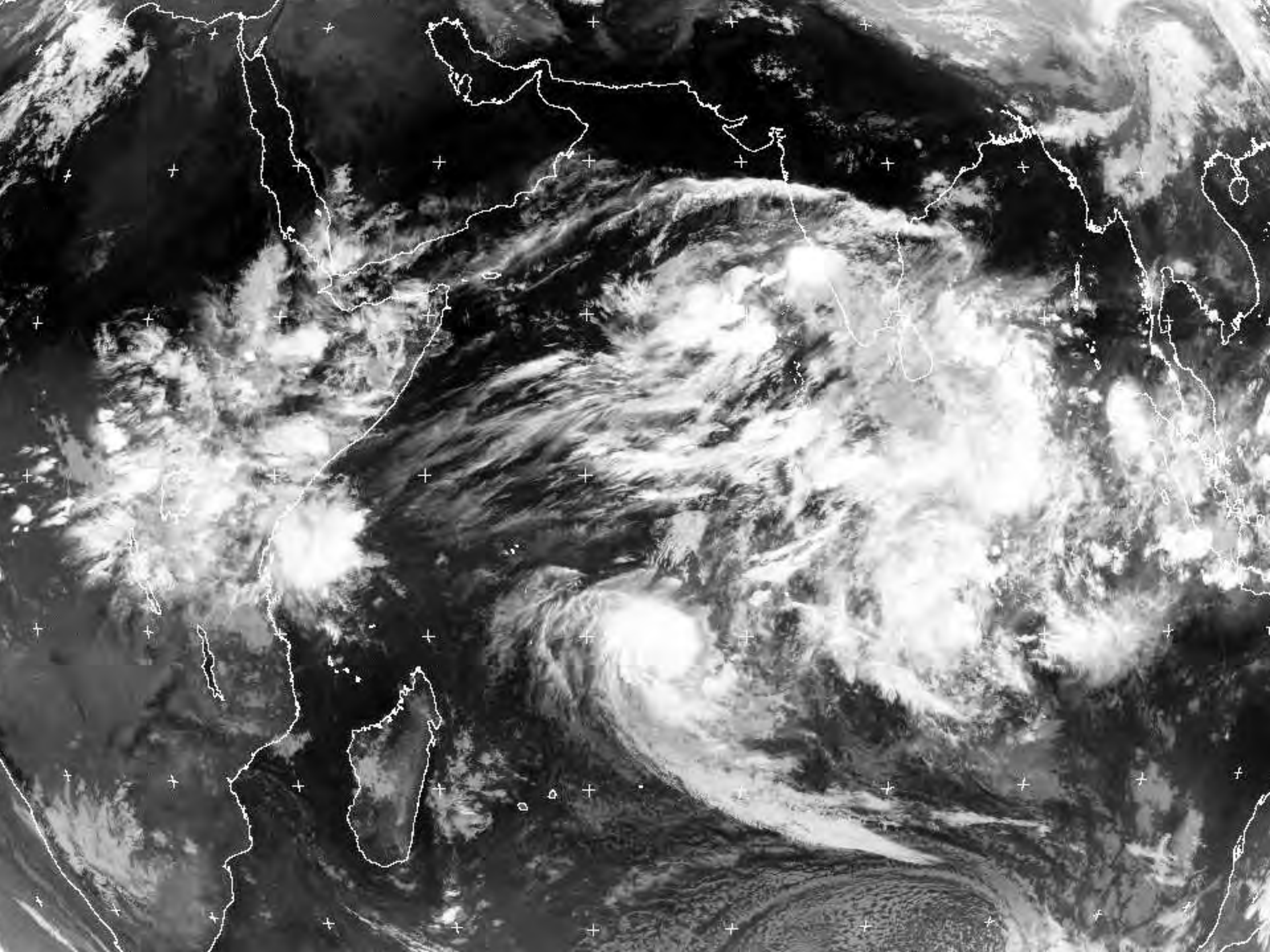


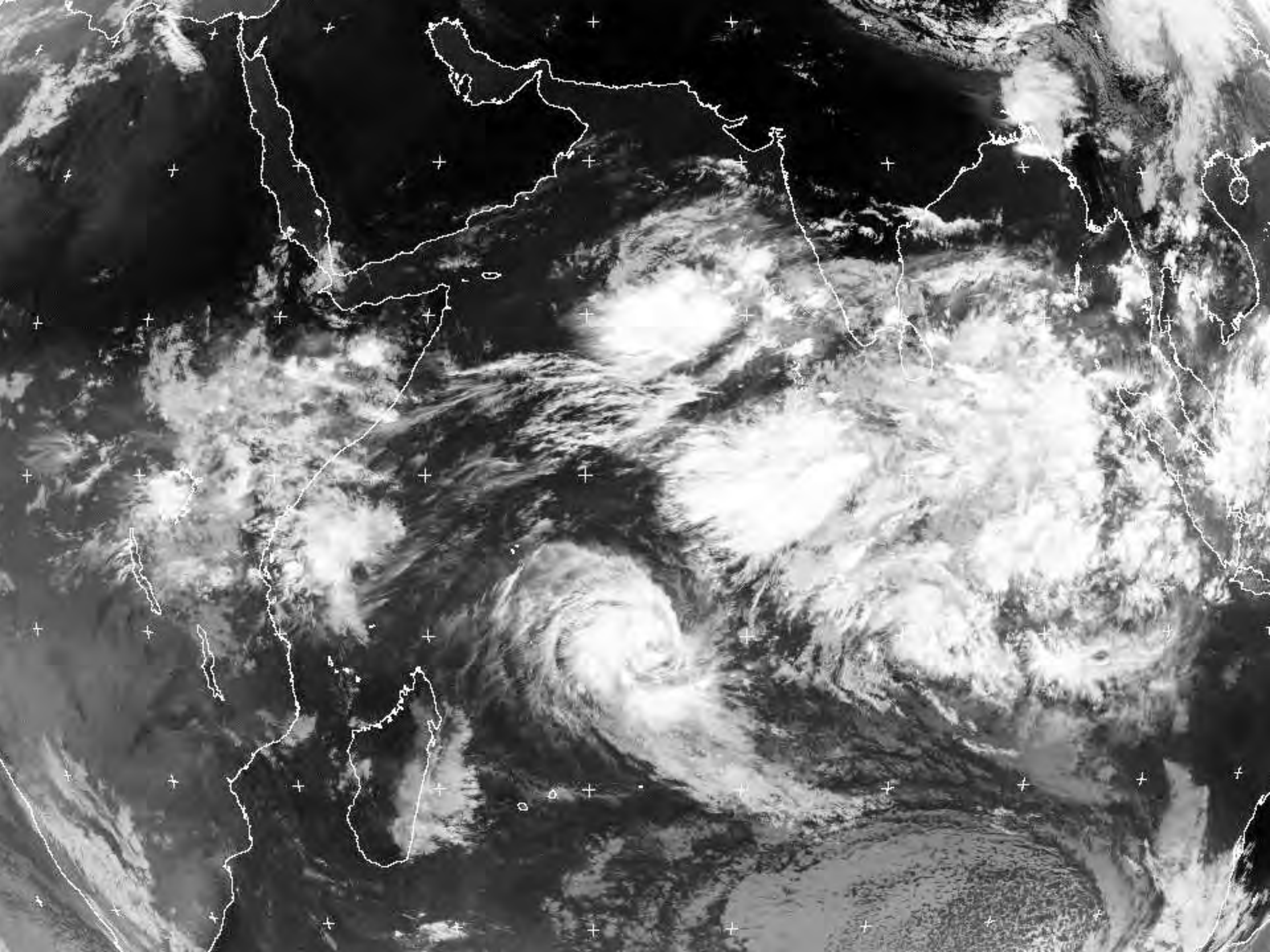


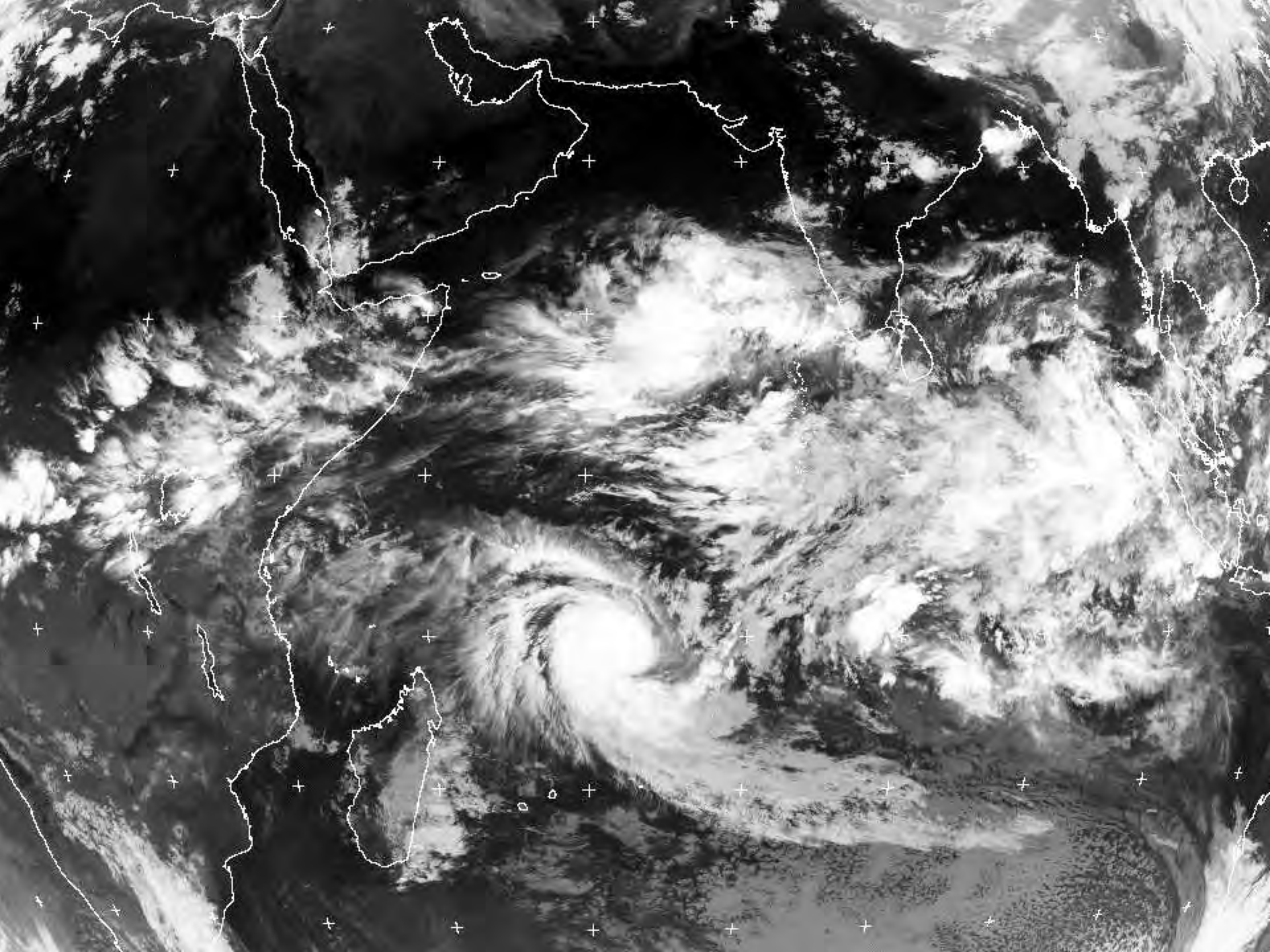


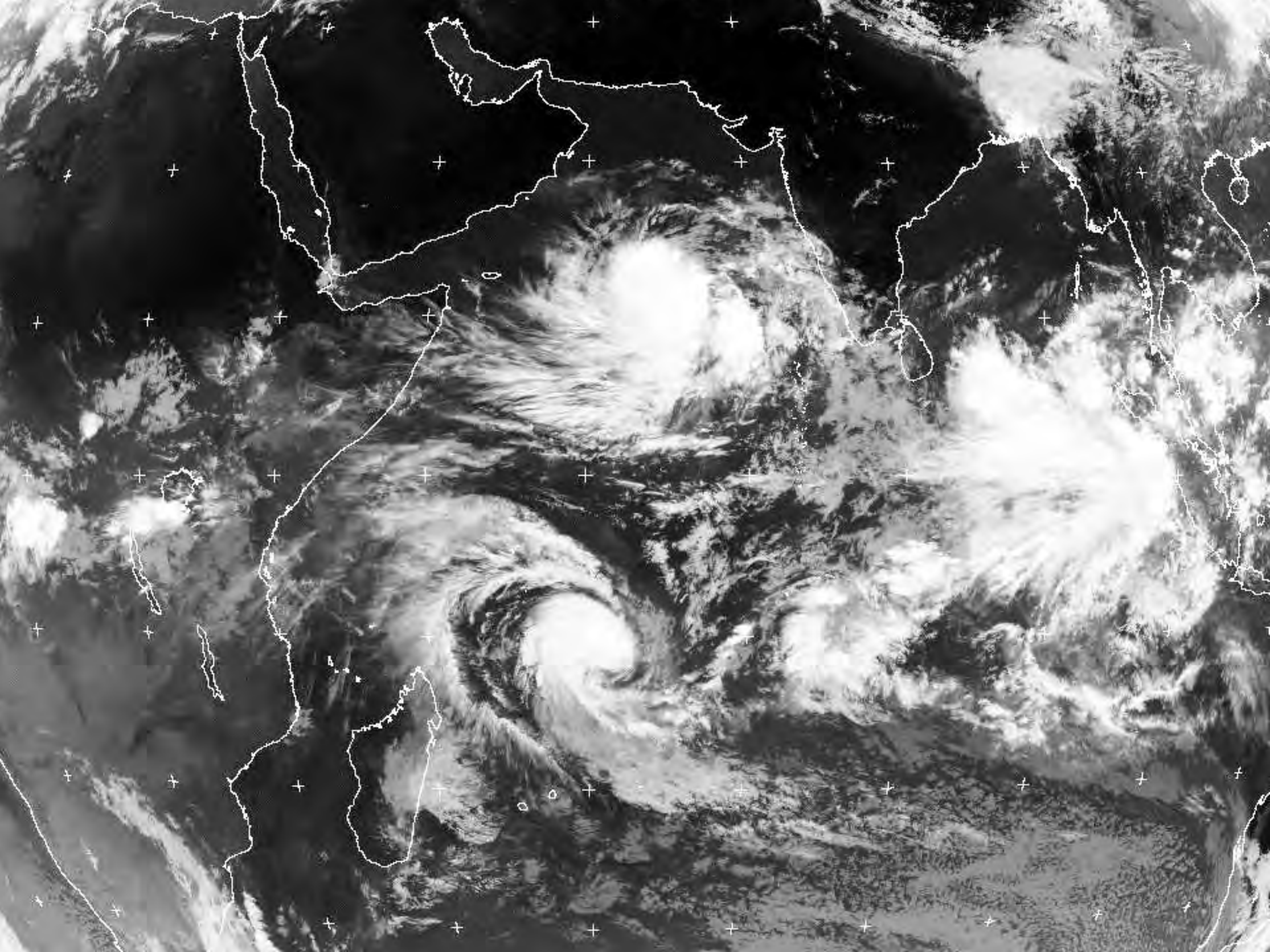


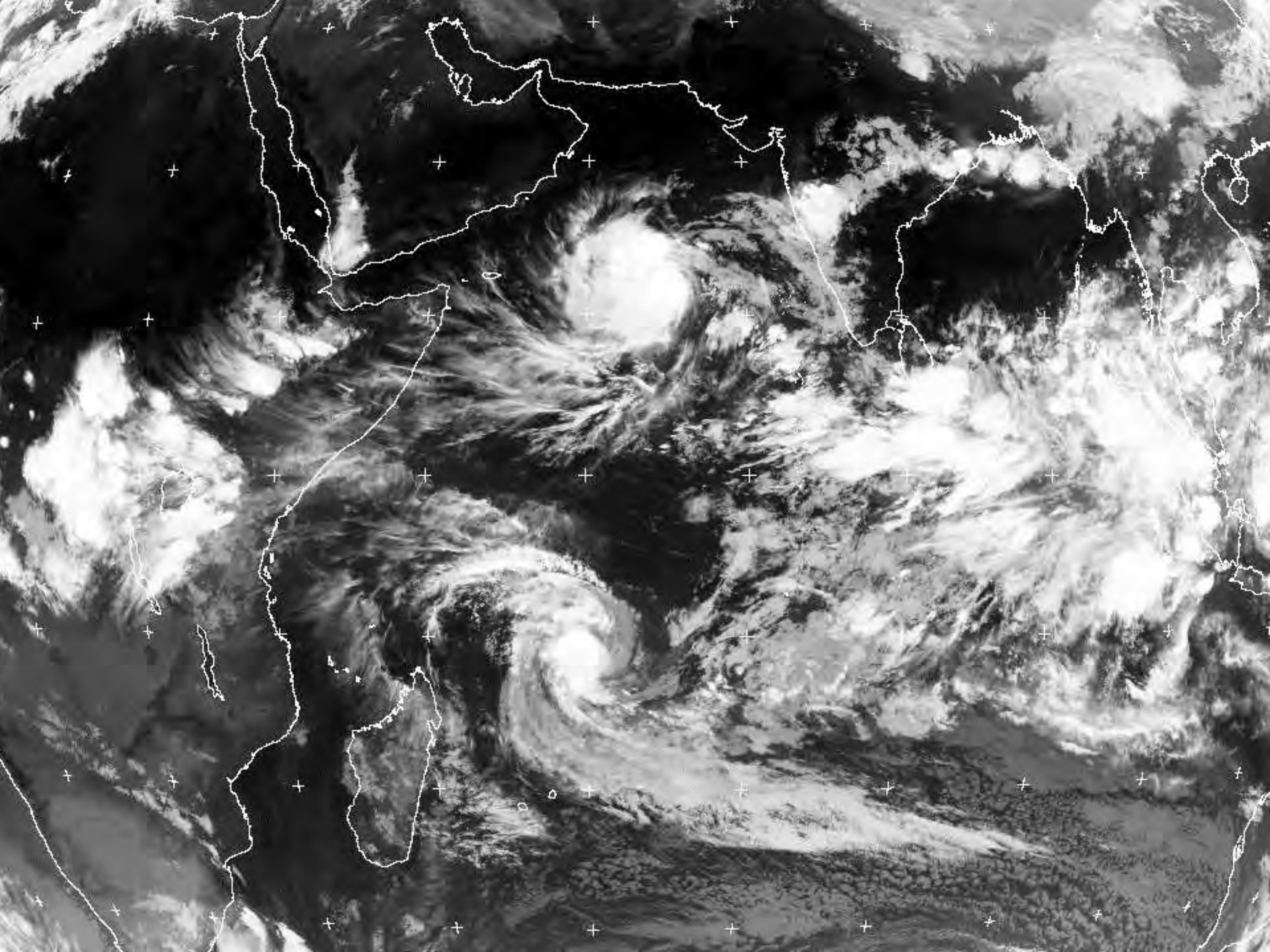


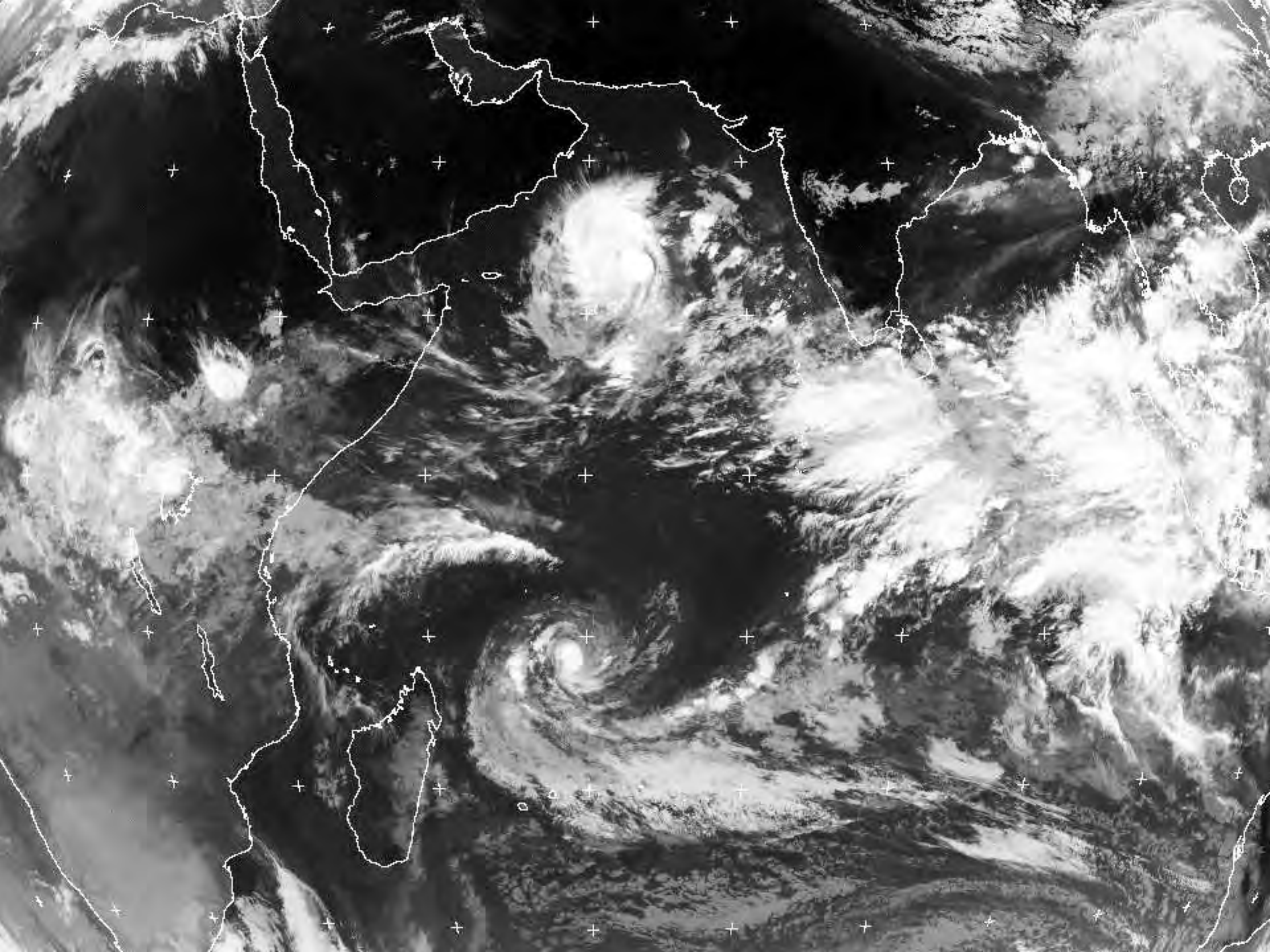


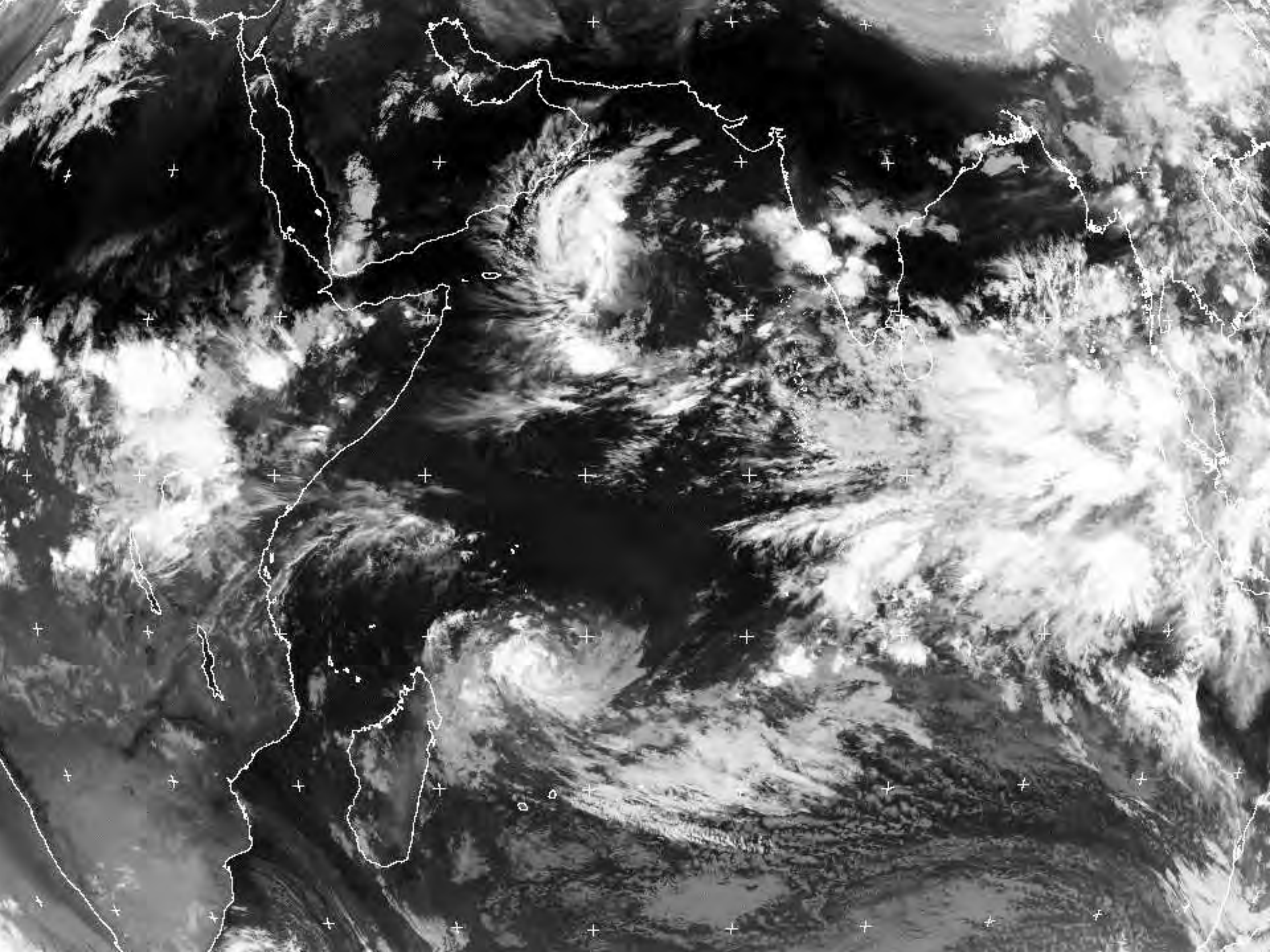


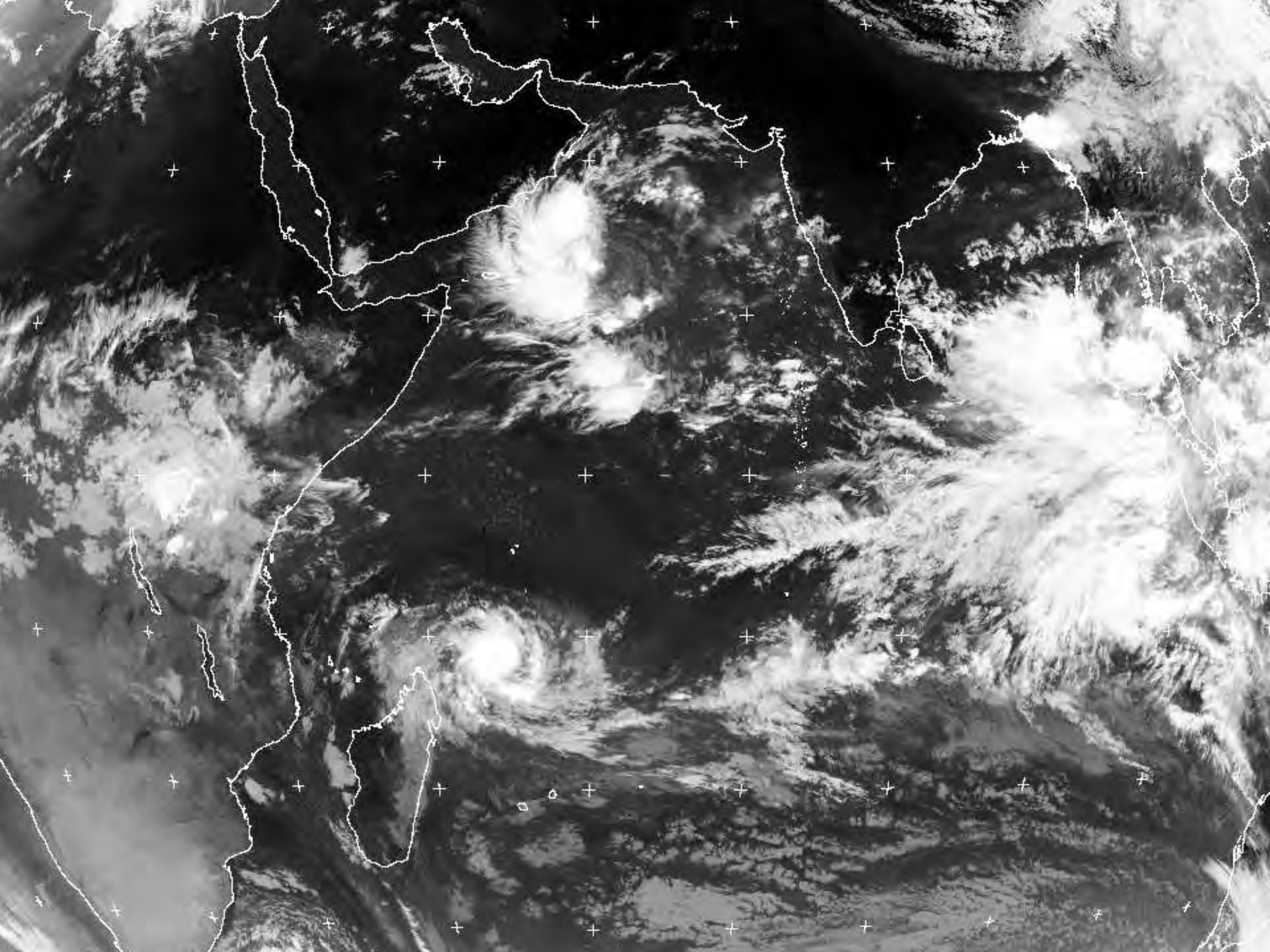


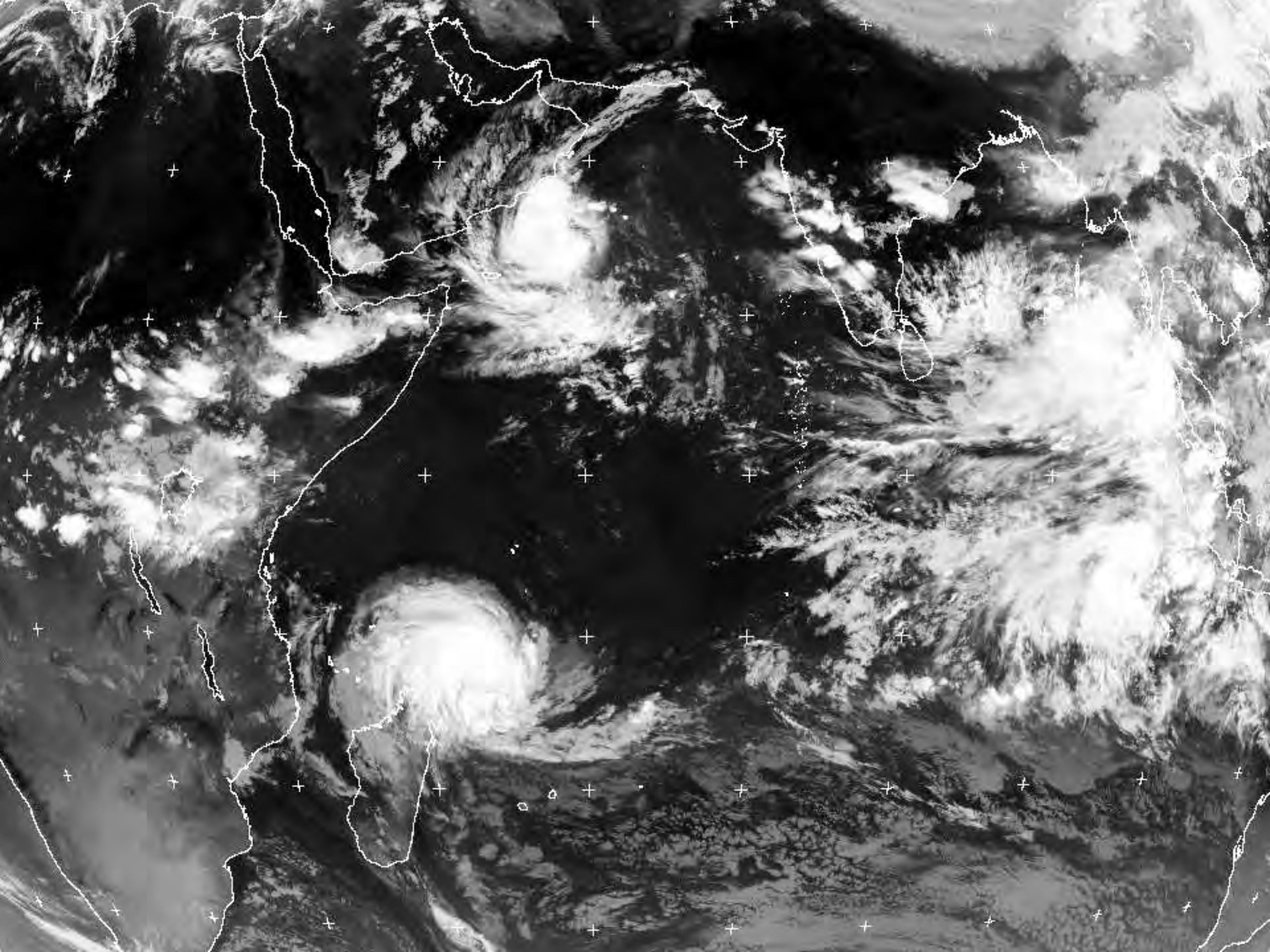


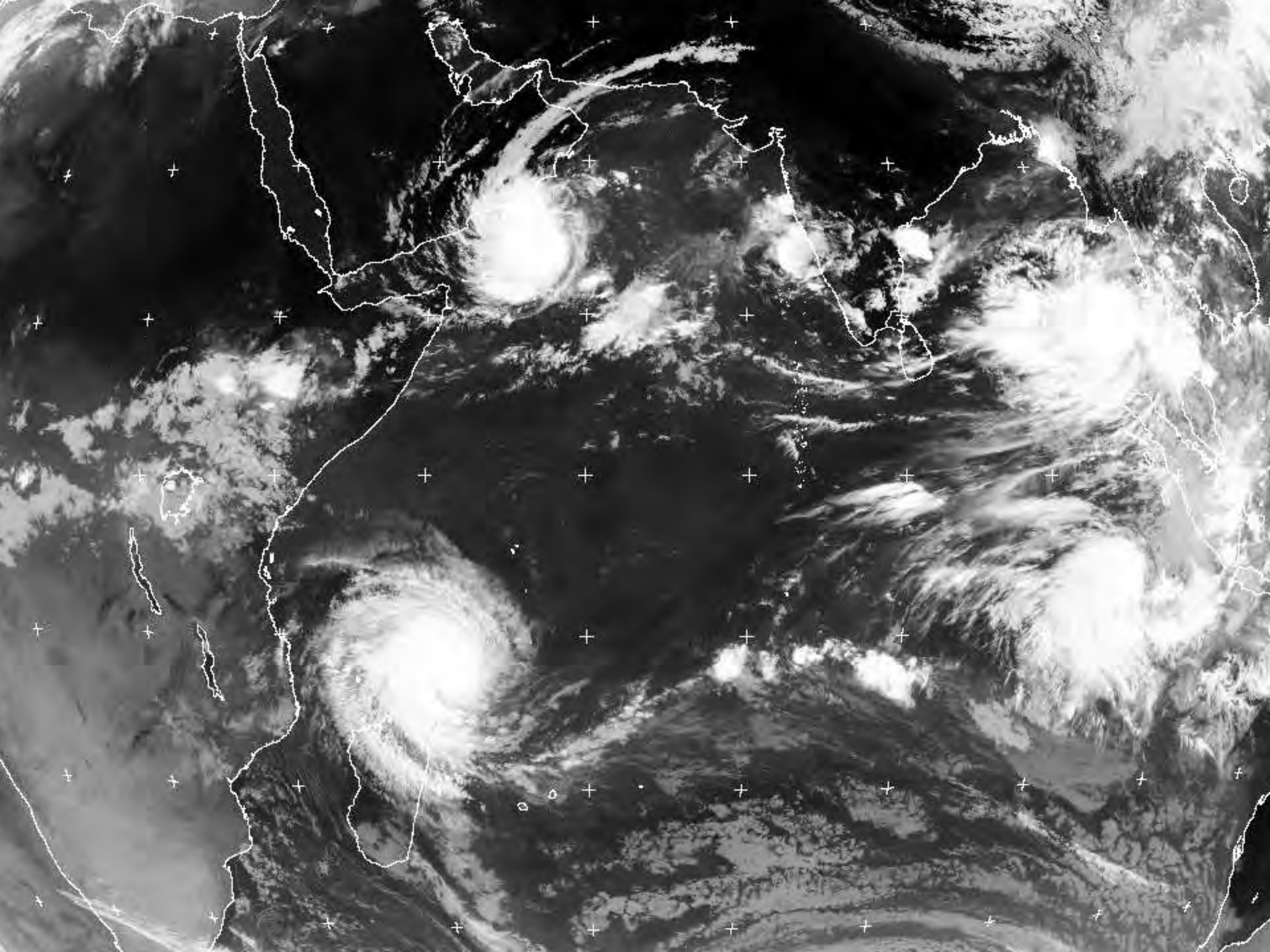


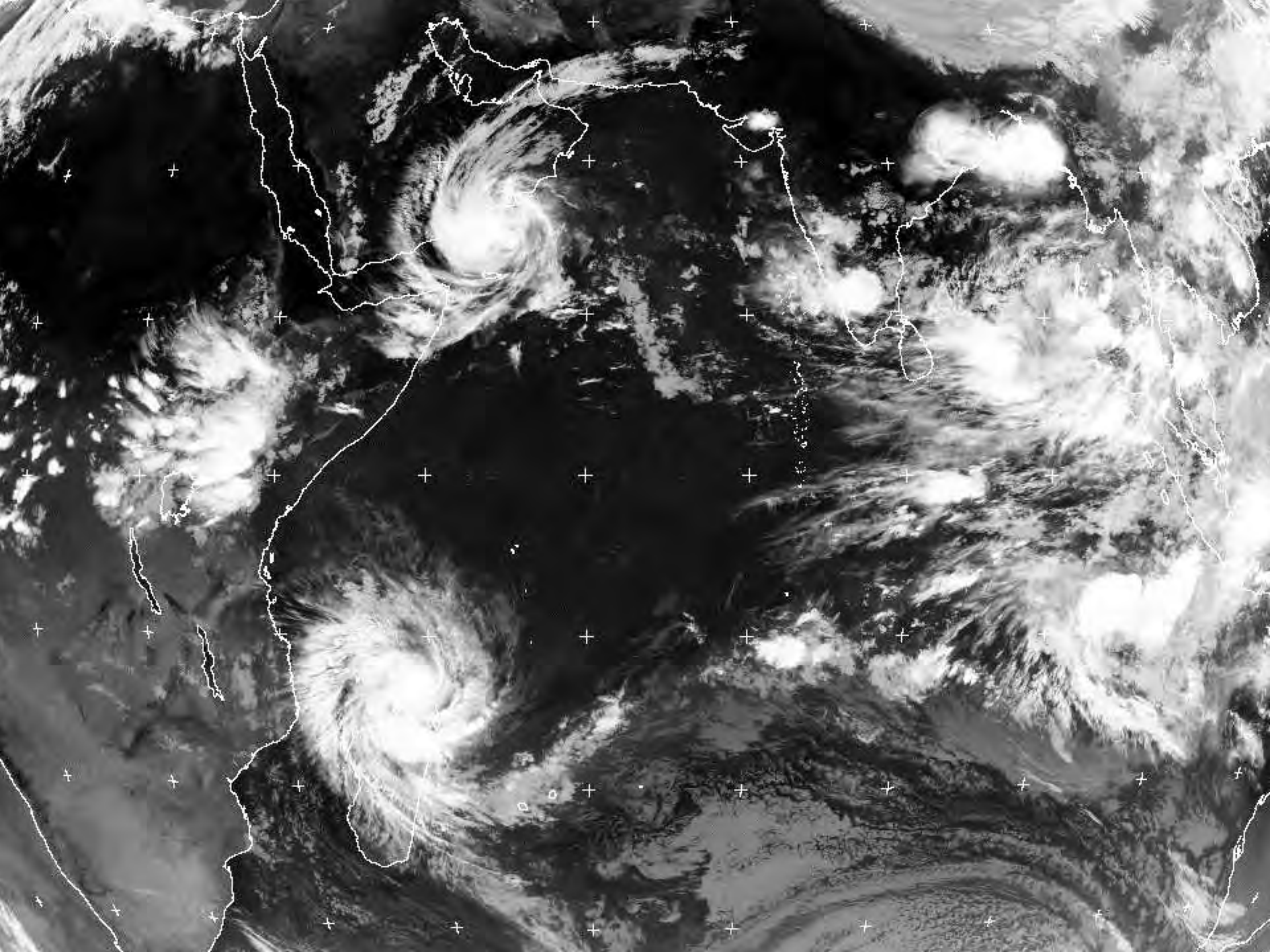


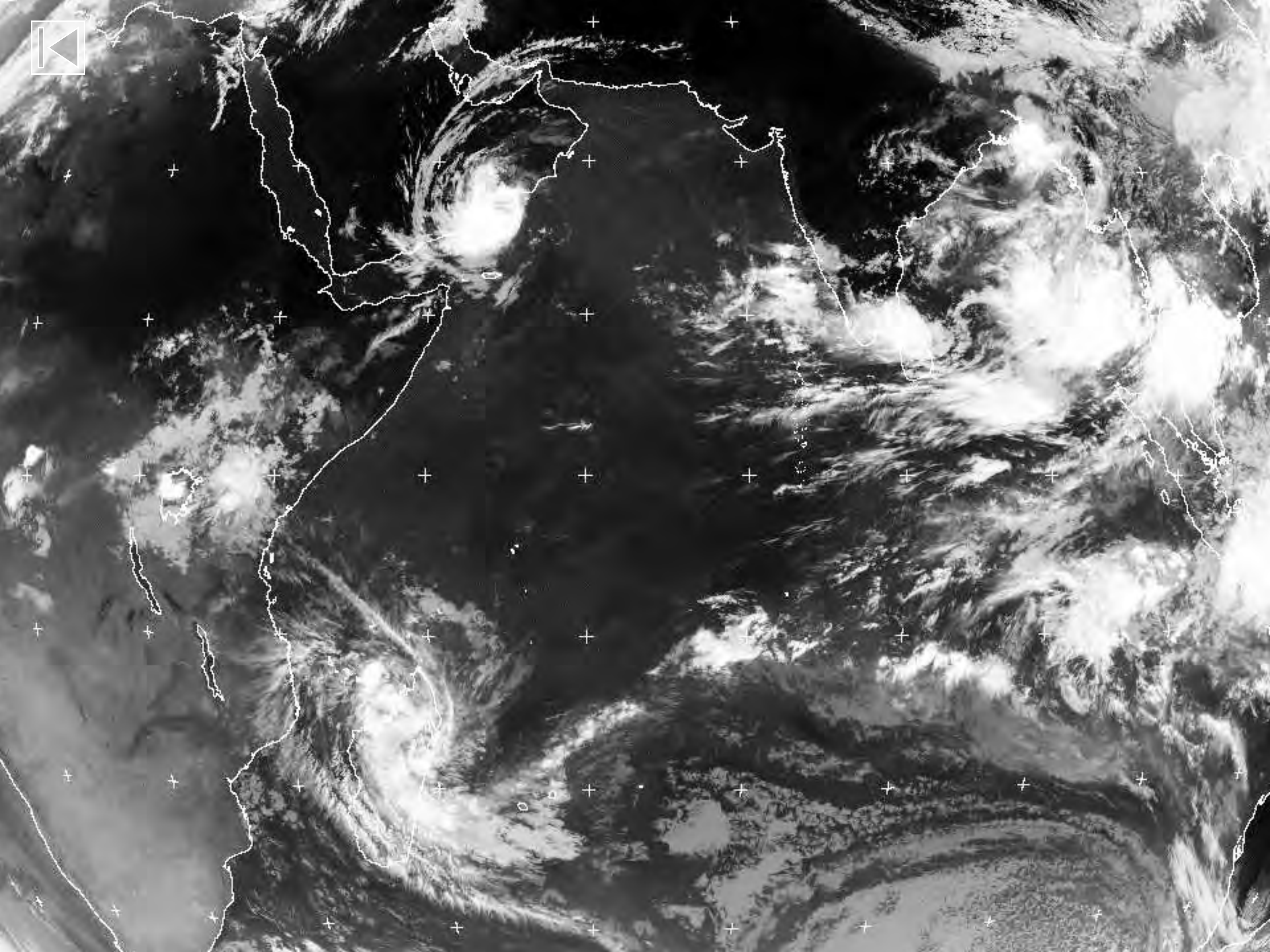




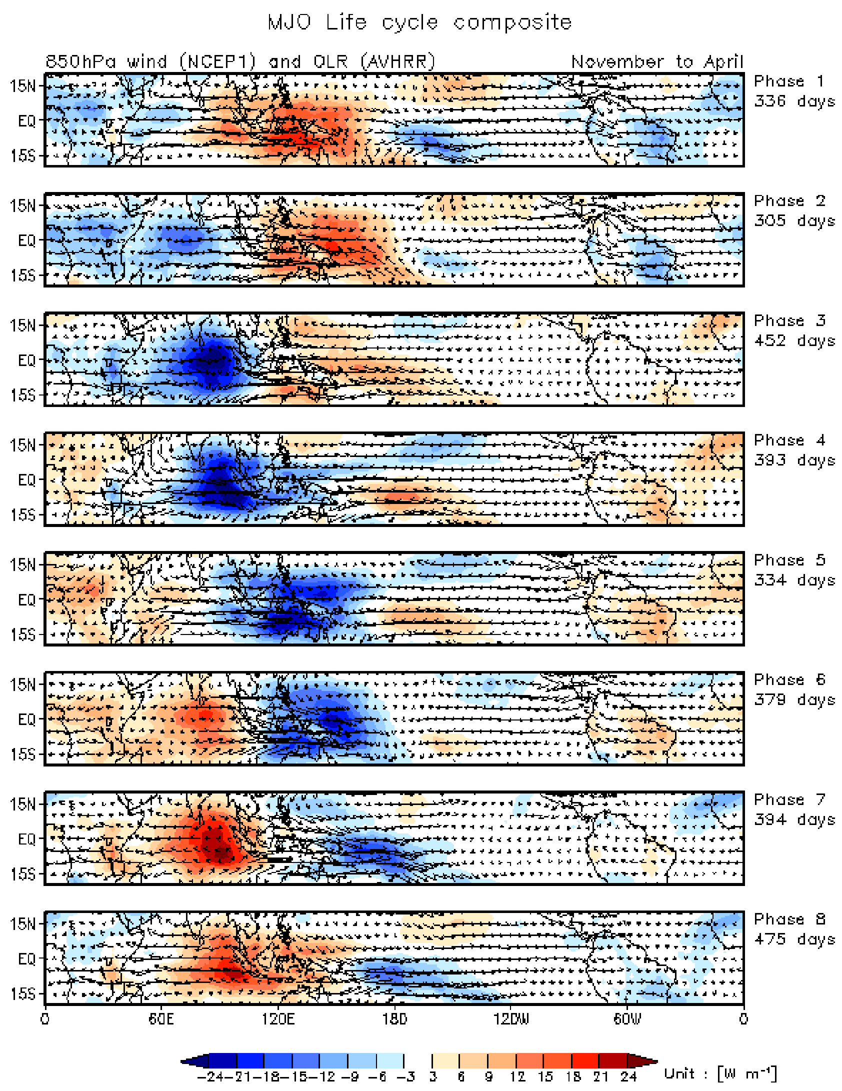








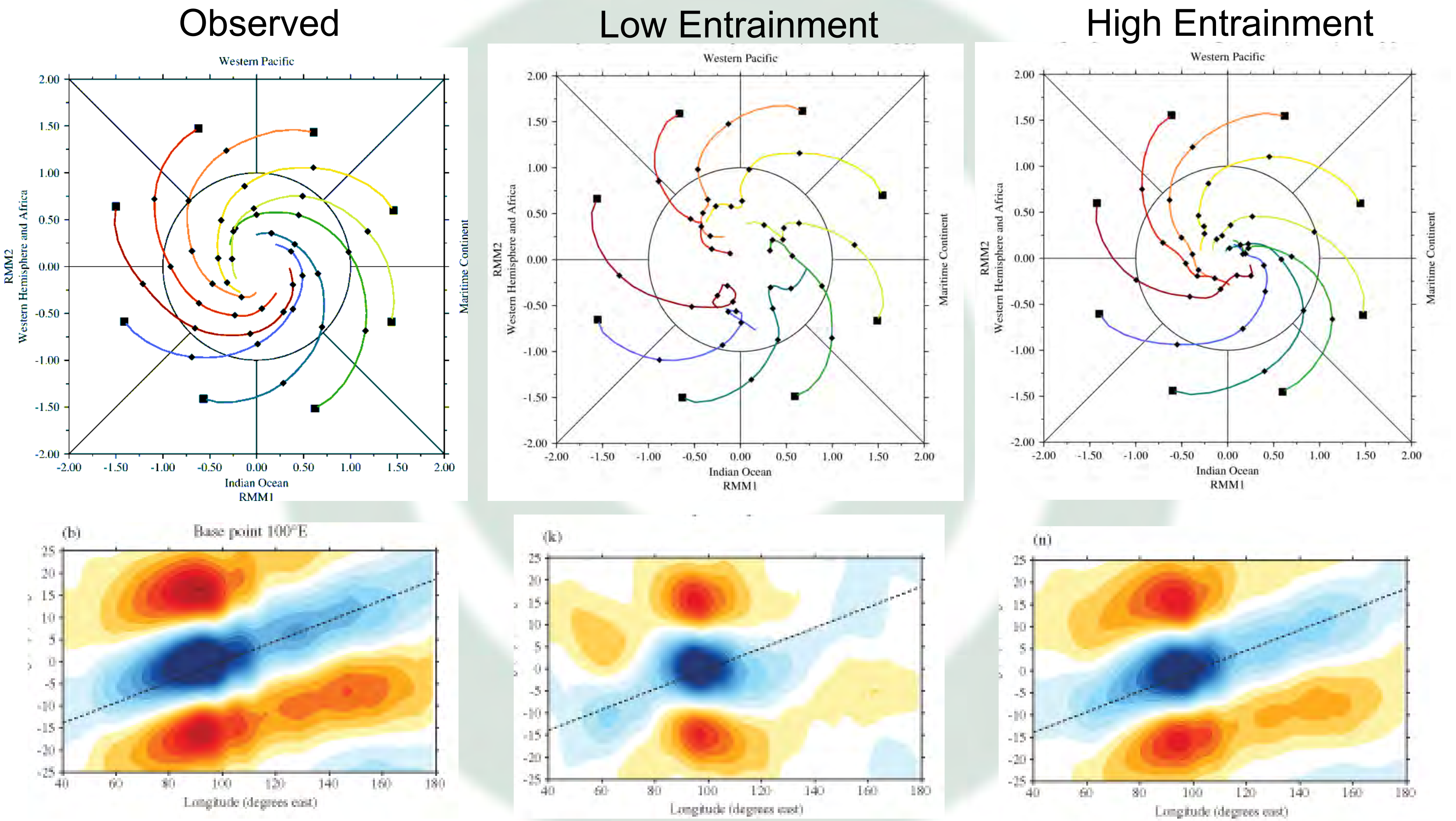
The Madden-Julian Oscillation



- Winter (Nov-Apr) composite of OLR and 850hPa winds
  - based on the multivariate index of Wheeler and Hendon (2004)
- Convective signal develops in Indian Ocean propagate eastwards and decays in the Central Pacific
- Low-level westerly anomalies behind the convection and easterlies ahead

Figure taken from US Clivar MJO WG Diagnostics Page
http://climate.snu.ac.kr/mjo_diagnostics/index.htm

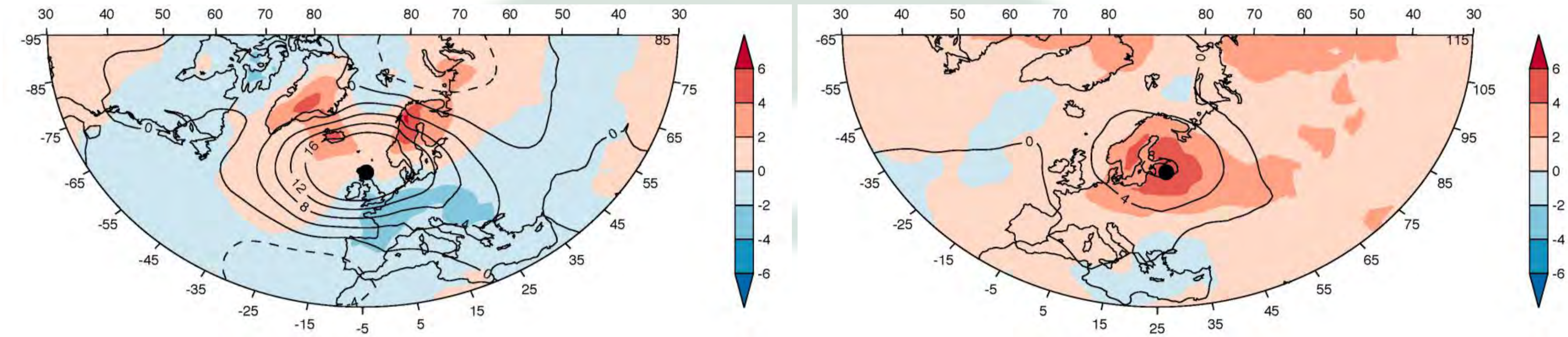
Sensitivity to the representation of convection: variability



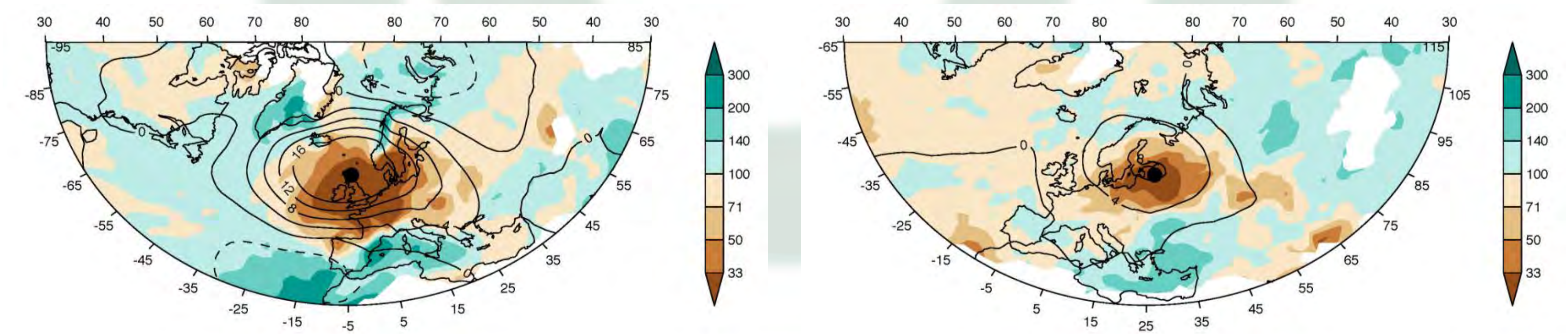
adapted from Klingaman and Woolnough (2014a,b)

Blocking

Temperature Anomaly



Precipitation Anomaly

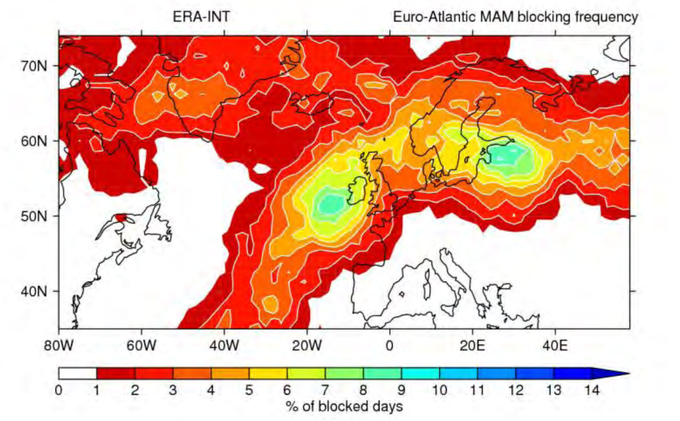


Winter **Spring**

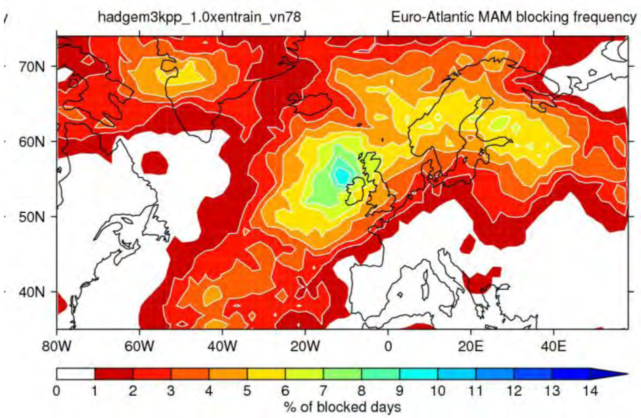
Figures courtesy of Reinhard Schiemann

Sensitivity to the representation of convection: variability

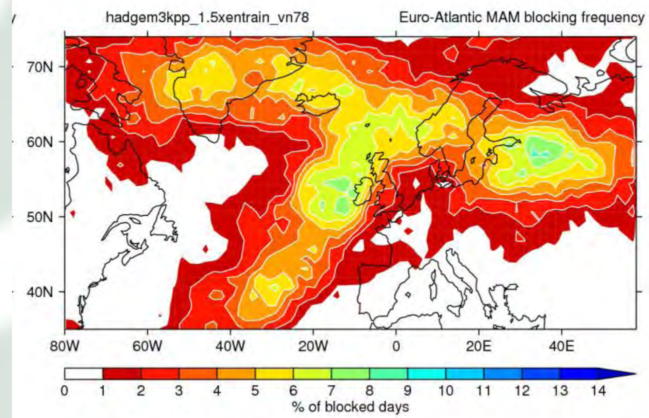
Observed



Low Entrainment



High Entrainment



Figures courtesy of Linda Hirons

Sensitivity to the representation of convection: variability

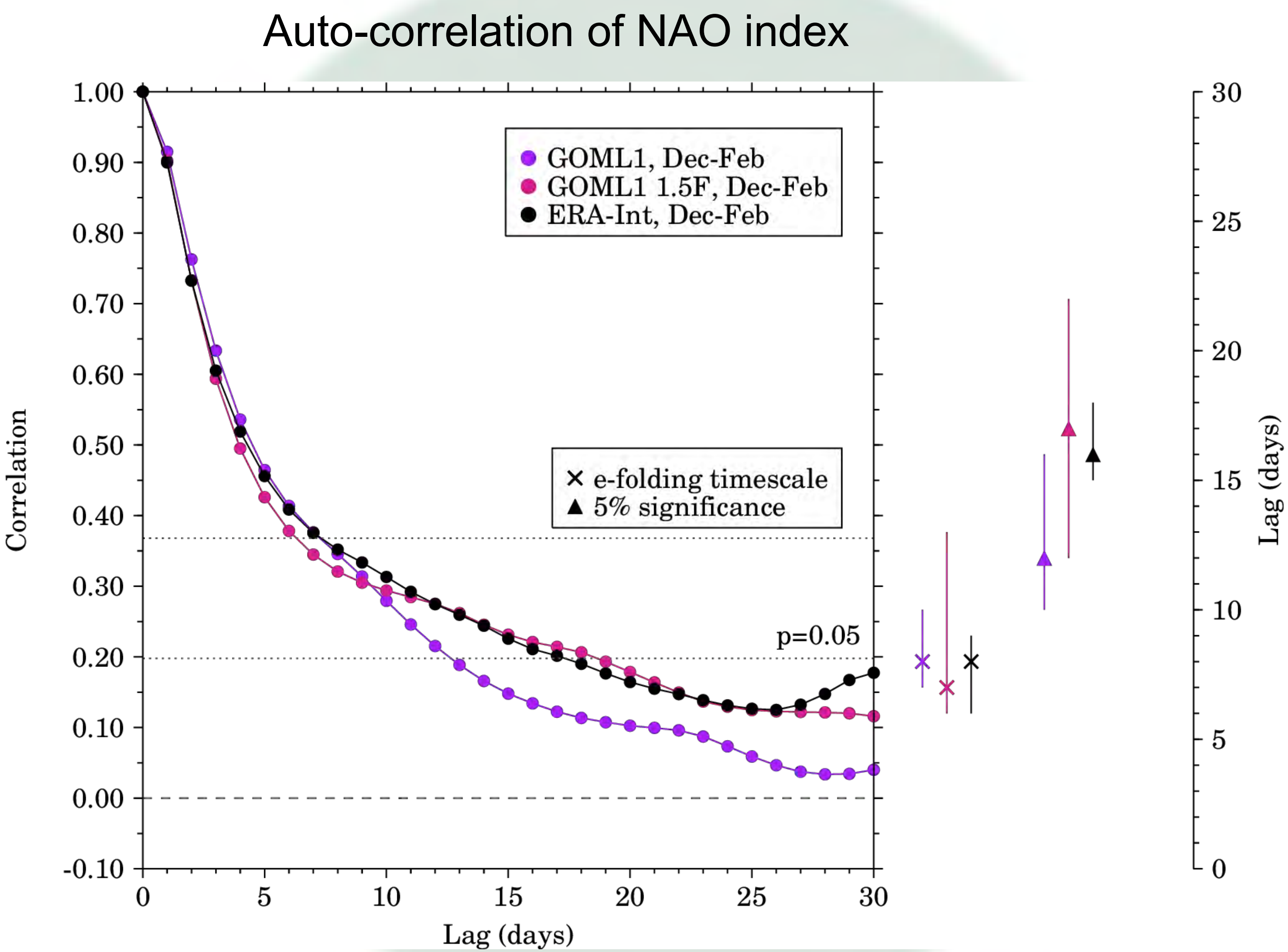


Figure courtesy of Nick Klingaman

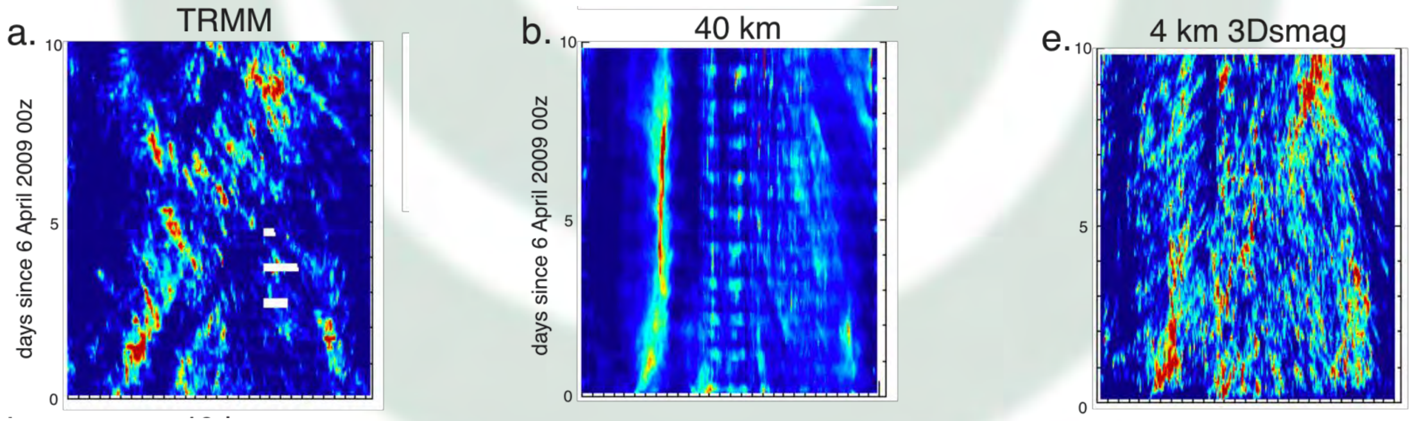
Resolution and Convection

Can resolution solve the problems with representing convection?

- We’re a long way from being able to resolve convection explicitly in our climate models, **however**

- We can now run simulations with explicit convection over large domains to understand e.g.,
  - how convection is organized across scales
  - what controls the temporal evolution of convection

  to improve our representation of convection in our climate models



Observations | 40km Resolution | 4km Resolution

from Holloway et al (2012)

Resolution and Convection

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  - what controls the temporal evolution of convection

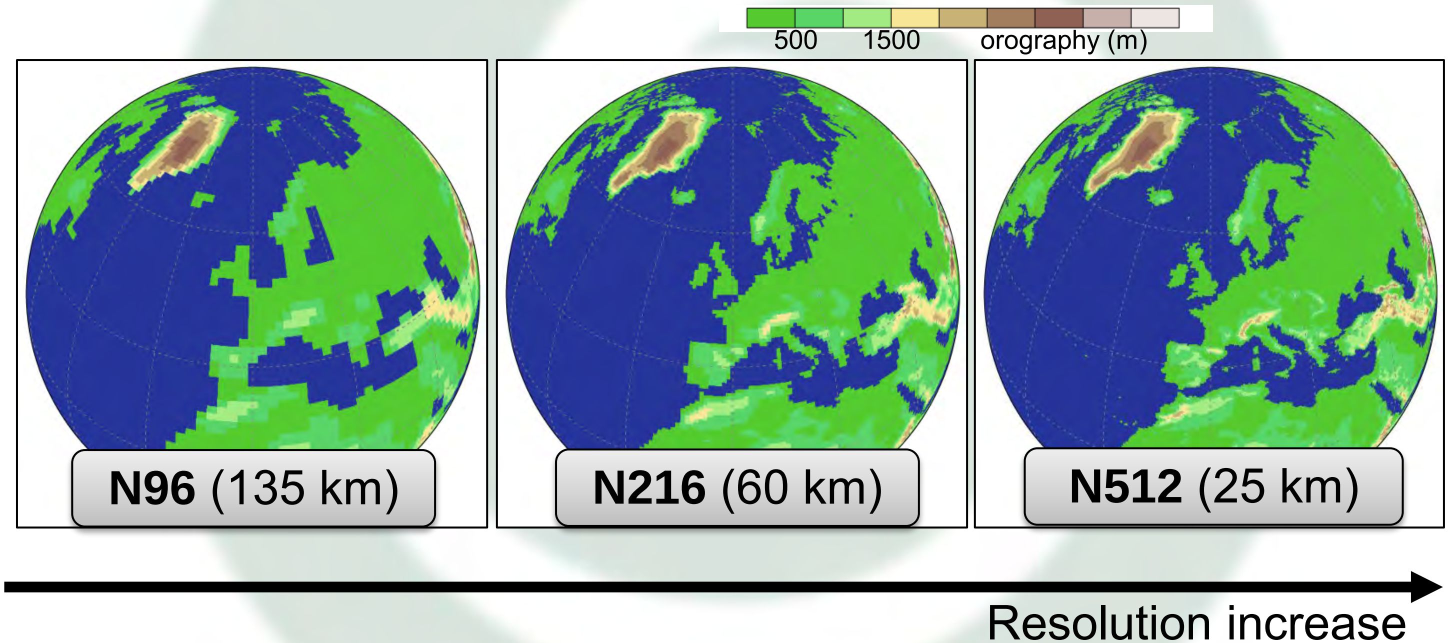
  to improve our representation of convection in our climate models

- The problem of the representation of convection in models is a major focus of national and international activity at the moment
  - WCRP Grand Challenge on Clouds, Circulation and Climate Sensitivity
  - Major German BMBF Funded Research Programme
    - High Definition Clouds and Precipitation for Climate Prediction – HD(CP)^2
  - New UK Joint NERC/Met Office Programme launched on
    - Understanding and Representing Atmospheric Convection across scales

Sensitivity to Resolution

Based on results from the UK JWCRP* High Resolution Climate Modelling Programme

(Pier Luigi Vidale , Reinhard Schiemann, Marie-Estelle Demory, NCAS; Malcolm Roberts, Matthew Mizielinski, Met Office)



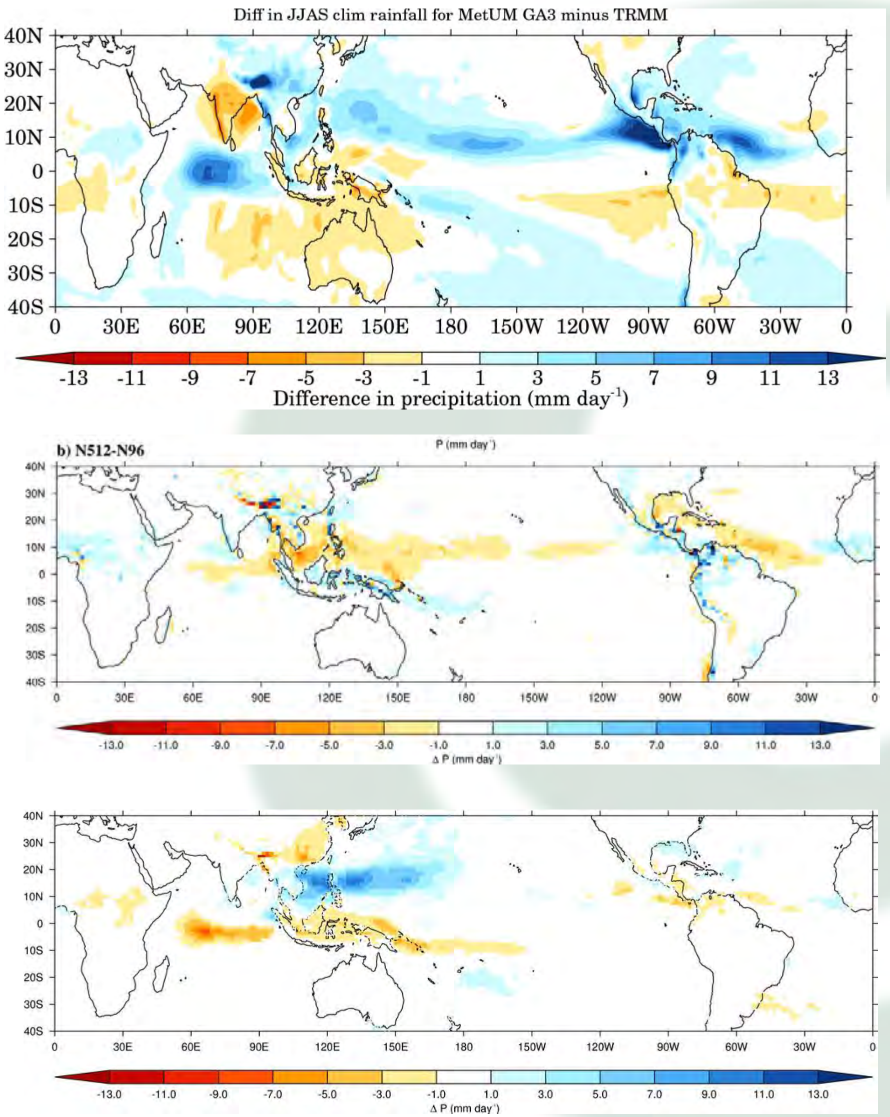
**Joint Weather and Climate Research Programme, a collaboration between the UK Met Office and the Natural Envrionmental Research Council*

Sensitivity to resolution: Tropical Precipitation Bias

Bias

Resolution

Entrainment



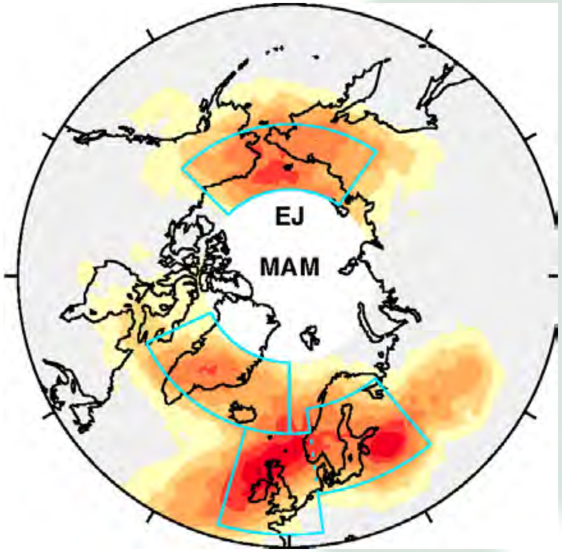
- Impact of resolution on tropical precipitation bias, Northern Hemisphere summer example
- Small impact of resolution in and around the Maritime Continent, likely associated with the impact of changes in the representation of orography, and land sea mask *(e.g. Schiemann et al. 2014, Bush et al. 2015)*
- Impact is comparable to the sensitivity to the representation of convective entrainment
- Generally resolution has a modest impact on mean state biases, perhaps larger changes in extra-tropics than tropics

Figures courtesy of Stephanie Bush

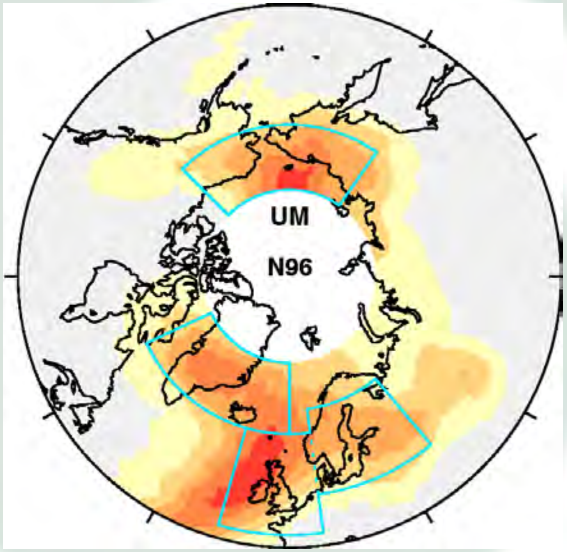
Sensitivity to Resolution: Variability

Significant Improvement in Spring Blocking in the Euro-Atlantic Section

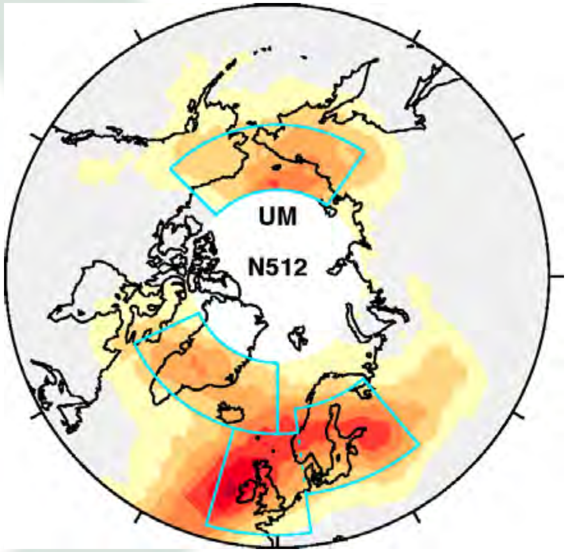
Observed



Low Resolution



High Resolution

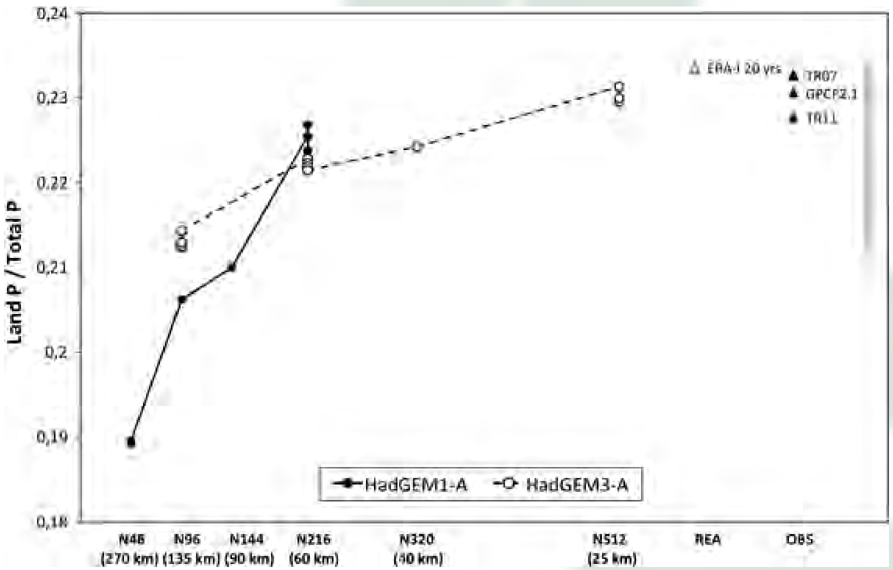


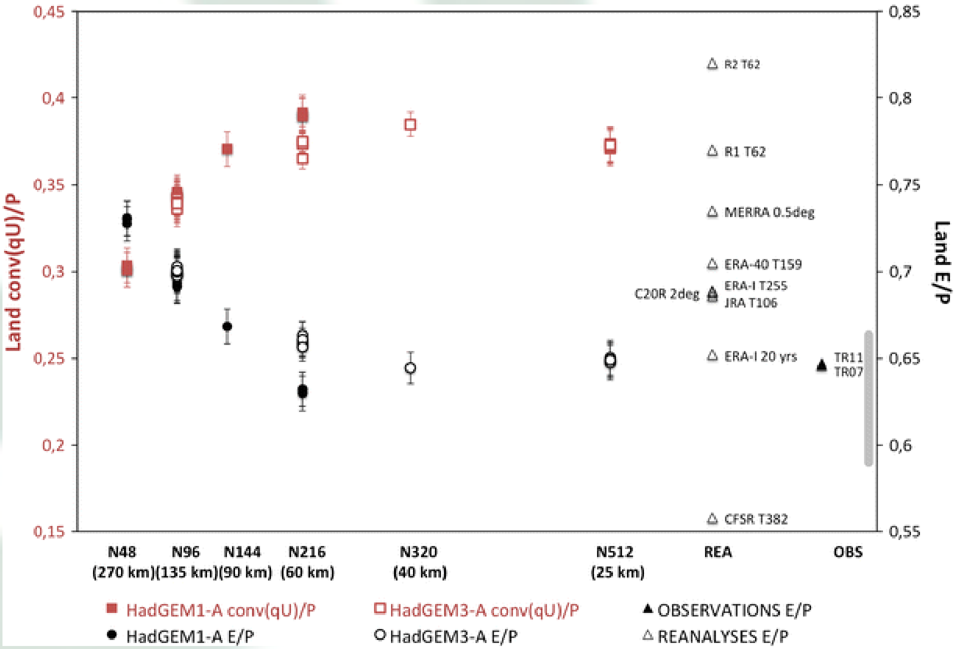
Figures courtesy of Reinhard Schiemann

Sensitivity to Resolution: Water Cycle

Significant Changes in the Water Cycle

- Increase in fraction of global precipitation falling over land
- Increase in transport of water from ocean to land
  - In tropics by the mean flow
  - In extratropics by the eddies (weather systems)





from Demory et al (2014)

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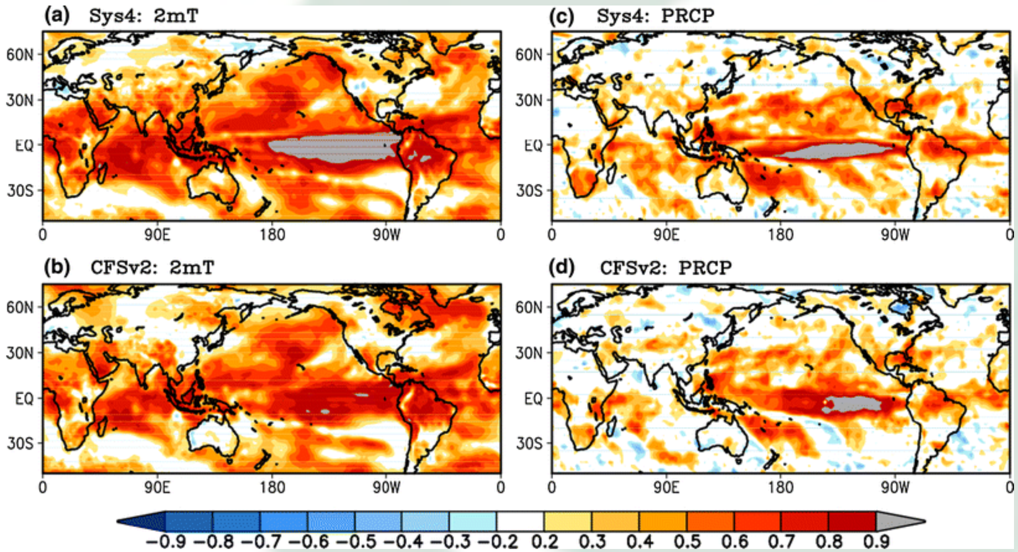
Seasonal and Sub-Seasonal Prediction

- **Seasonal Prediction;** Forecast lead times of 2-4 months (occasionally out to 7 months)
  - Skill comes primarily from slowly varying parts of the climate system, e.g.
    - SST, Sea Ice
    - Land surface conditions
- **Sub-seasonal Prediction;** Forecast lead times of 3-4 weeks
  - Skill comes from both slowly varying components of the system, e.g. and the initial state of the atmosphere
- Needs a coupled model
- Relies on a good representation
  - relevant modes of climate variability
  - teleconnection pathways in the atmosphere
- Forecasts typically issued as anomaly from a lead-time dependent model climatology to account for model bias in mean and variability
  - Ensemble mean anomalies
  - Quantile (e.g. tercile, quintile) probabilities

Seasonal Prediction

- Good skill for tropical temperature and tropical Pacific precipitation
- Some skill for extra-tropical temperatures over oceans, but little or no skill for extra-tropical precipitation



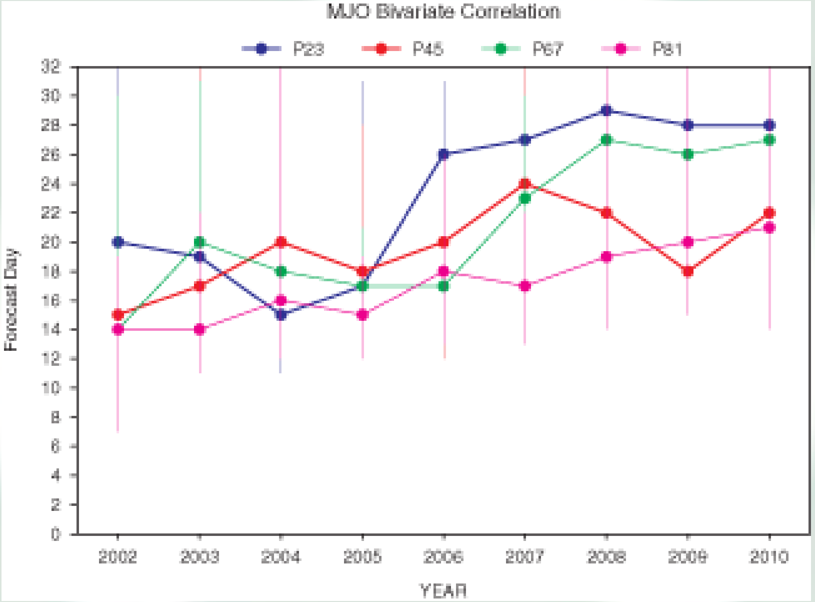
Correlation coefficients of
•2m temperature (left)
•precipitation (right)
for
•ECWMF Sys4 (top) and (bottom)
•NCEP CFSv2 (bottom)
for the period of 28 years from 1982 to 2009 winter
From Kim et al. (2012)

- Recently the Met Office are reporting improved skill for the North Atlantic and European Sector in their new system GLOSEA5 (Scaife et al, 2014)

Sub-Seasonal Prediction

An example from the ECMWF system

- Tropical Skill largely related to the MJO, improved MJO prediction skill over the last decade

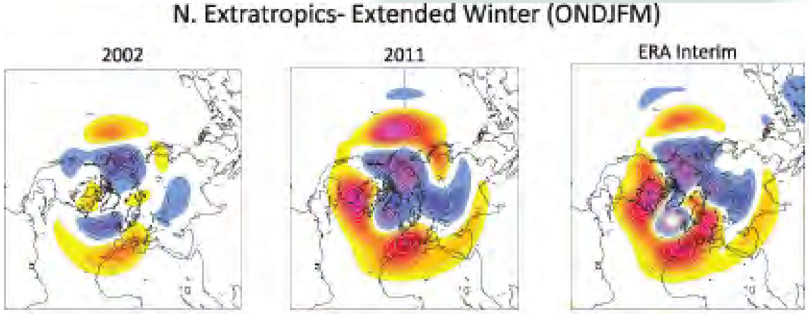


Evolution of the MJO skill scores since 2002 as a function of the phase of the MJO in the initial conditions. The curves represent the day when the MJO bivariate correlation reaches 0.6. From Vitart et al. (2012)

Sub-Seasonal Prediction

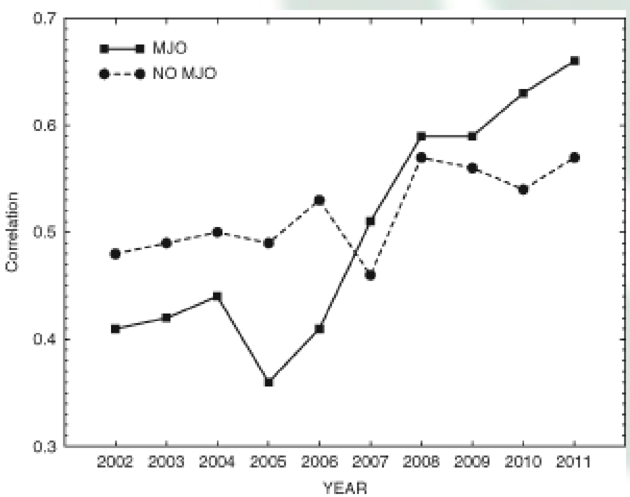
An example from the ECMWF system

- Strong teleconnection between the MJO and the NAO (Cassou, 2008); capturing this teleconnection relies on good predictions of phase and amplitude of MJO



MJO phase 3 10-day lagged composites of 500 hPa geopotential height anomaly over the Northern Extratropics for reforecasts that were produced in 2002 (left), in 2011 (centre) and ERA-Interim (right). From Vitart et al. (2012)

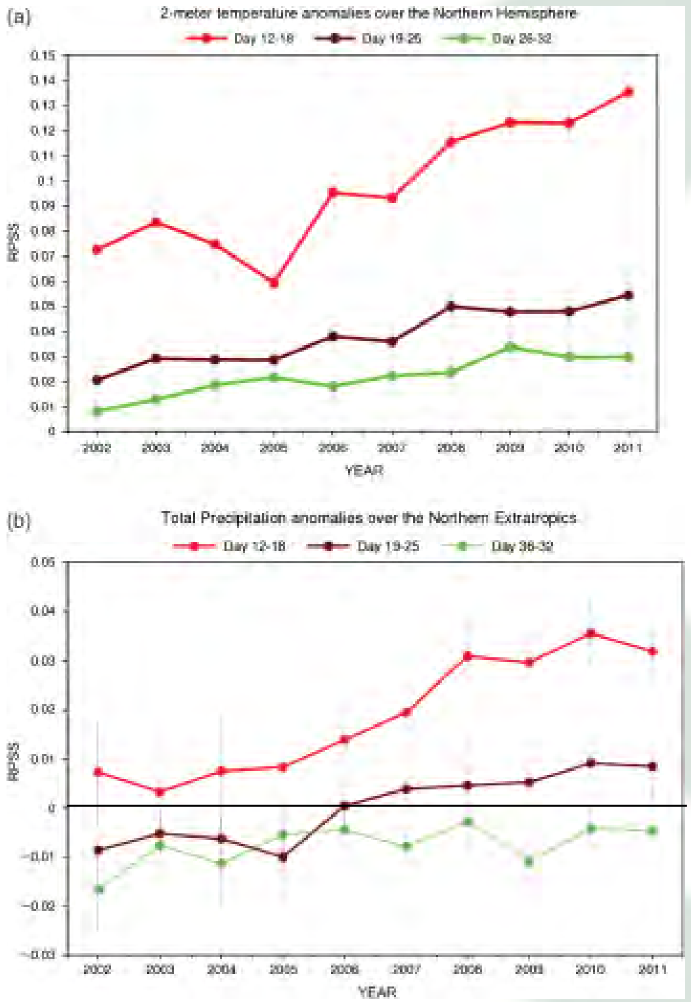
- Impact of improved MJO teleconnection on NAO forecast skill



Evolution of the ensemble mean NAO correlation with observed for lead times 19-25days for all the cases when there is an MJO in the initial conditions and when there is no MJO in the initial conditions From Vitart et al (2012)

Sub-Seasonal Prediction

An example from the ECMWF system



- Improving skill for Temperature and precipitaiton
- Skill for temperature at all lead times
- Skill for precipitation at days 12-18 and recently 19-25

Evolution of the discrete ranked probability skill score (RPSS) for weekly mean anomalies over land in the Northern Extratropics for
•2m temperature (top)
•Precipitation (bottom)
From Vitart et al (2012)

Sub-Seasonal Prediction: WCRP/WWRP S2S Project

- The World Climate Research Programme and World Weather Research Programme have recently launched a

Sub-Seasonal to Seasonal Prediction Project (S2S)

s2sprediction.net

- Objectives
  - To improve forecast skill and understanding on the subseasonal to seasonal timescale with special emphasis on high-impact weather events
  - To promote their exploitation by the applications community
- A database of near realtime operational sub-seasonal forecasts from 11 operational centres

  https://software.ecmwf.int/wiki/display/S2S/Home

  - Typically updated once a week out to lead times between 30-60 days

Sub-Seasonal Prediction: WCRP/WWRP S2S Project

10 metre u-velocity	Instantaneous once a day (00Z)
10 metre v-velocity	Instantaneous once a day (00Z)
Skin temperature	Daily averaged
Soil moisture top 20cm	Daily averaged
Soil moisture top 100 cm	Daily averaged
Soil temperature top 20 cm	Daily averaged
Soil temperature top 100 cm	Daily averaged
Surface air maximum temperature	6-hourly
Surface air minimum temperature	6-hourly
Surface air temperature	Daily averaged
Surface air dewpoint temperature	Daily averaged
Surface pressure	Instantaneous once a day (00Z)
Time-integrated surface latent heat flux	Accumulated, archived every 24 hours
Time-integrated surface net solar radiation	Accumulated, archived every 24 hours
Time-integrated surface net thermal radiation	Accumulated, archived every 24 hours
Time-integrated surface sensible heat flux	Accumulated, archived every 24 hours
Time-integrated surface solar radiation downwards	Accumulated, archived every 24 hours
Time-integrated surface thermal radiation downwards	Accumulated, archived every 24 hours
Total cloud cover	Daily averaged
Total precipitation	Accumulated, archived every 6-hours
Northward turbulent surface stress *	Accumulated, archived every 24 hours
Eastward turbulent surface stress *	Accumulated, archived every 24 hours
Water runoff and drainage *	Accumulated, archived every 24 hours
Surface water runoff *	Accumulated, archived every 24 hours

Sub-Seasonal Prediction: WCRP/WWRP S2S Project

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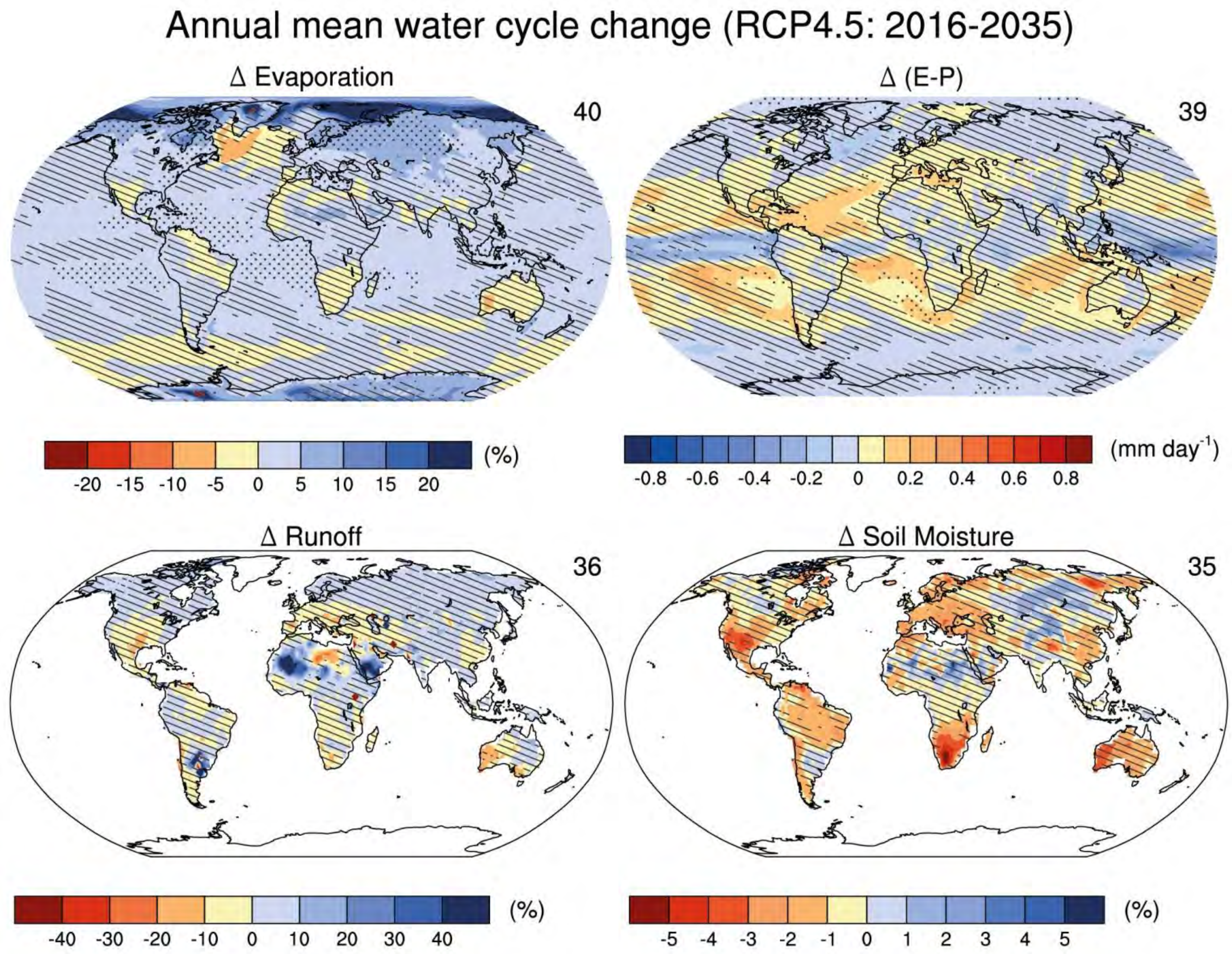
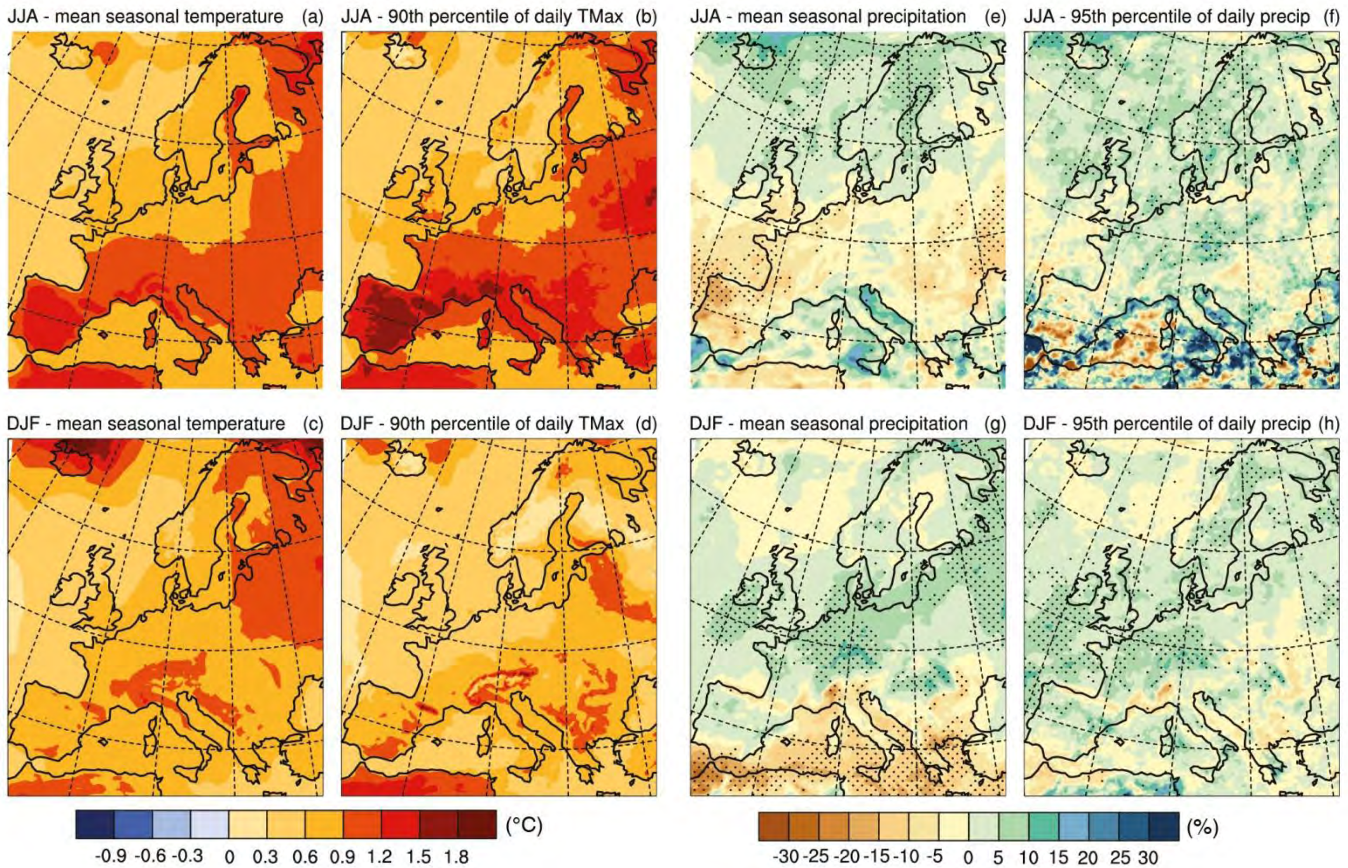
  https://software.ecmwf.int/wiki/display/S2S/Home
  - Typically updated once a week out to lead times between 30-60 days
- Research Foci on
  - Evaluation, Windows of opportunity
  - Monsoons, The Maritime Continent, Africa
  - Extremes
  - Teleconnections

Change in the Water Cycle



From Fig 11.14 of the IPPC AR5 WG1 Report

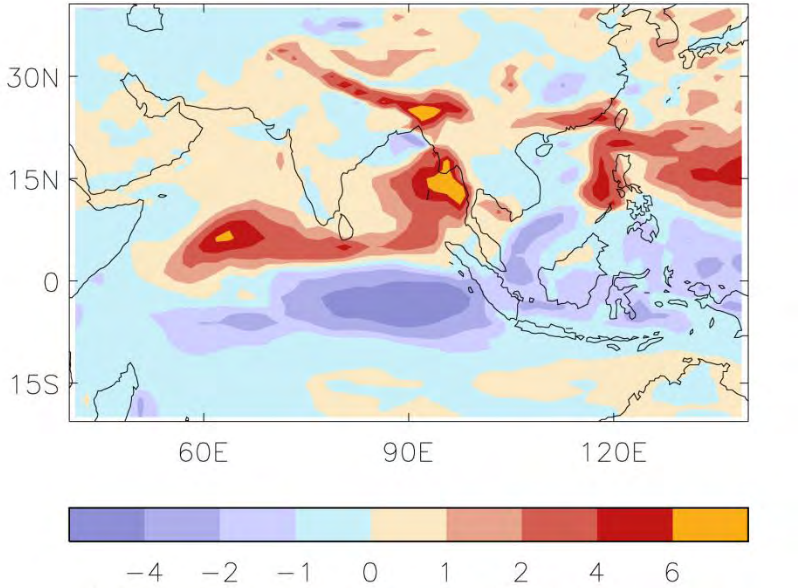
Change in Extremes



European-scale projections from the ENSEMBLES regional climate modelling project for 2016–2035 relative to 1986–2005, with top and bottom panels applicable to JJA,DJF respectively. For temperature, projected changes (°C) are displayed in terms of ensemble mean changes.
The stippling in (e–h) highlights regions where 80% of the models agree in the sign of the change (for temperature all models agree on the sign of the change). The analysis includes 10 GCM-RCM simulation chains for the SRES A1B scenario. (Rajczak et al., 2013.)

Fig 11.18 of the IPPC AR5 WG1 Report

“Climate Change”

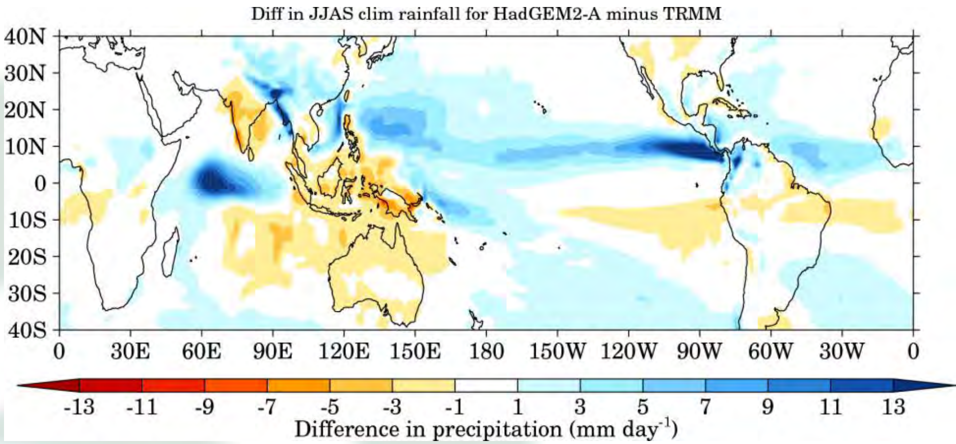


From Martin and Levine (2013)

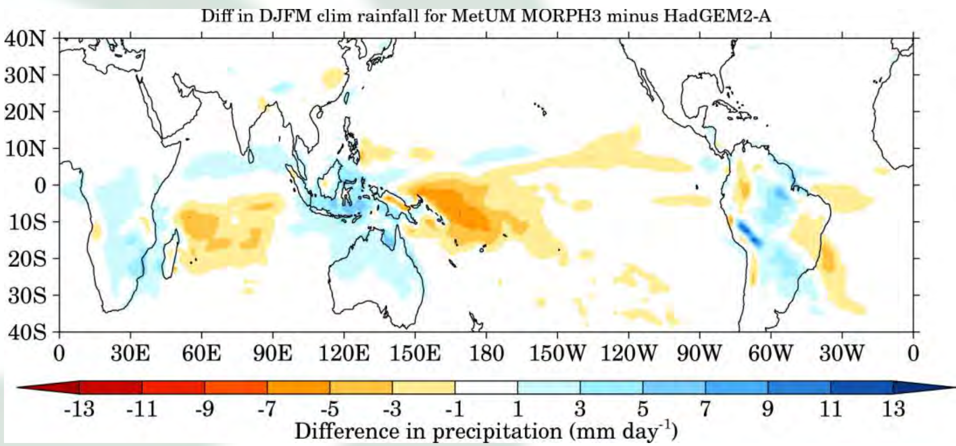
Change from present day in a time-slice experiment using change in SST and GHG from RCP8.5 at 2100 cf

- the model bias
- the change going to the next version
- the change in one parameter (of a different version)

Bias



Next Model



One parameter